

Attachment B

Contamination Containment and Controls Working Group Results and Homework

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Contamination Containment and Control

1. Limit Contaminant Toxicity and Mobility

1.4a Engineer Biogeochemical Environment (source contaminants)

Target: Deploy alternate technologies that detoxify or immobilize risk-driving contaminants at the source.

1.4b Engineer Biogeochemical Environment (ground water environment)

Target: Deploy alternate technologies that reduce the volume of ground water that would otherwise have been pumped and/or treated.

2. Limit Intrusion, Transport, Release, and Exposure

2.2a Design, build, and operate alternate containment systems (cover barriers)

Target: Deploy cover systems that mimic natural processes and accommodate environmental change.

2.2b Design, build, and operate alternate containment systems (subsurface barriers)

Target: Deploy subsurface containment systems that mimic natural processes and accommodate environmental change.

4. Predict, Monitor, and Evaluate System Performance

4.1 Conceptualize and predict system performance and potential failure modes / levels of failure.

Target: Deploy a “toolbox” of techniques and technologies (e.g., models, natural analogues, guidance, performance indicators, failure criteria, etc.) to improve planning, decision making, design, monitoring, maintenance, and interpretation of monitoring data.

5. Maintain System Performance

5.1 Identify and implement improved responses to change (via routine and preventative maintenance that nurtures system performance) and failure (via corrective repair, retrofit, and replacement).

Target: Deploy technologies and protocols that significantly reduce the need for maintenance intervention of installed contamination containment and control system.

S&T Development Baseline Approach

The traditional waterfall model is the natural way of managing the development of something innovative and complex. In using the waterfall model the project proceeds according to clearly defined phases; a preceding phase must be completed before the next starts; phase completion is judged by the outcome of the phase matching the requirements defined by the previous phase. The phases of the traditional model are:

1. Concept
2. Feasibility analysis
3. User Definition of System Requirements
4. Developer Definition of System Requirements
5. High-Level Design
6. Detailed Design
7. Prototype development
8. Integration and Test
9. System Test
10. Acceptance Test
11. Operations
12. Maintenance.

1. Limit Contaminant Toxicity and Mobility

Technical Approaches (Form A)

Capability to be improved: 1.4a Engineer Biogeochemical Environment (source)

Associated Target(s): 1.4a Deploy alternate technologies that detoxify or immobilize risk-driving contaminants at the source.

Technique/technology # 1

Title: Soil Vapor Extraction

Current maturity level: SVE consists of an array of extraction wells, screened within the zone of contamination, that are equipped with an extraction pump capable of pulling enough air to maintain a vacuum within the zone of influence. Soil gases are pulled off and directed into a process train, which treats the gases prior to emission to the atmosphere. The system can be run intermittently (pulsed) once the extracted mass removal rate has leveled off. Pulsed operation can increase the effectiveness of the process. SVE addresses only volatile and some semi-volatile contaminants, and may enhance biodegradation of low-volatility organic compounds. A geosynthetic material may be required over the surface during this process to prevent short circuiting (break-through at the ground surface). Soil that has a high percentage of fines and a high degree of saturation will require higher vacuums and/or will hinder operation of the process. Application in soils with highly variable permeabilities may exhibit uneven delivery of gas flow resulting in less effectiveness in the lower permeability areas (FRTR 2001).

Range of Applicability: Effective at reducing volatile and semi-volatile organic contaminants in the subsurface. Preferentially removes materials from high permeability zones in the subsurface, but can be pulse-operated to allow diffusion to increase removal. Not effective for non-volatile organics, most inorganics, and radionuclides.

Needed R&D:

Sources:

FRTR, 2001, Federal Remediation Technologies Roundtable, *Remediation Technologies Screening Matrix and Reference Guide Version 3.0*. (Information also available at <http://www.frtr.gov>, updated 12-13-2001.)

Technique/technology # 2

Title: Low Pressure Grouting

Current maturity level: Permeation grouting involves injecting low viscosity grout formulations into the subsurface under gravity feed or low pump pressures. The grout permeates porous media and has been shown to encapsulate waste debris. Previously proven grouts include colloidal silica, polysiloxane, ultra-fine cement-based grouts, and polyacrylamide.

Range of Applicability: Very low permeabilities can be achieved in homogeneous media. At heterogeneous sites, it is difficult to ensure consistent applications across the subsurface. This process depends on the permeability, microstratigraphy, and porosity of the formation to be grouted (Hayward Baker 2001) and is most effective in media with homogeneous characteristics.

Needed R&D:

Sources:

Hayward-Baker, 2001, Permeation Grouting, ISSMFE-TC-17, available at: http://www.tc17.poly.edu/Permeation_Grouting.htm.

Technique/technology # 3

Title: Injection (High Pressure) Grouting

Current maturity level: Jet grouting involves use of a positive displacement pump to deliver grout to a drill rig, which injects the material into the waste zone through the drill string at 6000 pounds per square inch (psi) (400 bar). A thrust block—a massive concrete template with spaced holes and a void space beneath— can be used to ensure the grid spacing is maintained and workers are protected from returning contaminated grouts. The grout may be injected as the drill casing is inserted or as it is removed from full depth. The process requires site characterization and material testing to determine a suitable grouting agent. Many different grouts are available, including chemical grouts, which are injected as solutions rather than suspensions of particles in a fluid medium which defines cementitious grouts (USACE 1995). For long-term stabilization, a dense, low-porosity grout can be used to chemically and physically bind the waste.

Range of Applicability: Injection grouting has been demonstrated to significantly reduce hydraulic permeability. In addition, certain grout types chemically alter infiltrating water, reducing the solubility potential of contaminants. Grouting also minimizes landfill subsidence, which improves the performance of low-permeability cover systems. As with other in situ techniques, verification that all areas have been uniformly treated is difficult. This necessitates long- term monitoring of leachate to ensure protectiveness.

Jet grouting can be used effectively in soil types ranging from gravel to heavy clays (Mutch et al. 1997). Jet grouting has been repeatedly demonstrated on soil and waste sites.

Needed R&D: Techniques to control the potential spread of contamination resulting from contaminated grout returns have not yet been demonstrated.

Sources:

Mutch, R. D., R. E. Ash, and R. J. Caputi, 1997, “Contain Contaminated Groundwater,” *Chemical Engineering*, Vol. 104, No 5, pp. 114-119.

USACE, 1995, *Engineering and Design – Chemical Grouting*, EM 1110-1-3500, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, January 31, 1995. (Also available at: <http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-1-3500/toc.htm>.)

Technique/technology # 4

Title: Enhanced Soil Mixing

Current maturity level: In Situ Enhanced Soil Mixing is a process that has been used to remediate soils contaminated with volatile organic compounds, especially those of fine-grained nature. A single-blade auger or a combination of augers ranging from 1 to 4 m (3 to 12 ft) in diameter is used to mix the soils. This process option is combined with a number of other process options to either remove or stabilize contaminants of concern in place. The four main options for soil mixing include combination with vapor extraction and ambient air injection; vapor extraction and hot air injection, hydrogen peroxide injection; and grout injection for solidification/stabilization.

Range of Applicability: Effective at treating contaminants of concern depending on the combination of processes used. With soil vapor extraction, the mixing can be used to enhance stripping action. In situ peroxidation oxidizes volatile organic compounds (VOCs), while mixing cement grout under pressure can solidify the subsurface mass.

Needed R&D: Auger systems have to be tested under site-specific conditions to determine their performance under the given geologic conditions.

Sources:

Technique/technology # 5

Title: Soil Flushing

Current maturity level: Water is applied to the soil (sometimes with an additive to enhance contaminant solubility). Contaminants are dissolved into the pore water, extracted through wells, and then sent through a treatment train. Co-solvent flushing is an adaptation of soil flushing that uses a solvent mixture (e.g., water plus a miscible organic solvent such as alcohol). The target contaminant groups include inorganics (including radioactive contaminants), though VOCs, semi-volatile organic compounds (SVOCs), fuels, and pesticides may also be treated.

Range of Applicability: The process is more applicable to coarse-grained soil conditions (FRTR 2001). The process involves flushing water through the contaminated zone so potential contamination spreading and nuclear criticality hazards could limit its acceptability.

Needed R&D:

Sources:

FRTR, 2001, Federal Remediation Technologies Roundtable, *Remediation Technologies Screening Matrix and Reference Guide Version 3.0*. (Information also available at <http://www.frtr.gov, updated 12-13-2001>.)

Technique/technology # 6

Title: Chemical Leaching

Current maturity level: Contaminated wastes are leached with an appropriate leaching solution and the elutriate is collected in a series of shallow well points or subsurface drains. This process option is more commonly performed as an ex situ technology, eliminating concerns about toxicity of residual leachant.

Range of Applicability: The process is only effective in areas of relatively high permeability and on contaminants that have relatively high solubility. Also, the process is not effective for waste zones that are in contact with fractured rock vadose zones due to difficulties associated with collection of the elutriate.

Needed R&D:

Sources:

Technique/technology # 7

Title: Hydrolysis

Current maturity level: Hydrolysis is used to break down certain chemicals by reacting them with water.

Range of Applicability: Many pesticides, including aliphatic halides, amides, carbonates, and others, are susceptible to partial decomposition by hydrolysis (McBride 1994). Additionally, the process has been used for degradation of explosives and has been investigated for immobilization of radioactive elements (Nash 2000).

Needed R&D: Little data about the effectiveness of the process during in situ remediation efforts has been collected. Additionally, contaminant-specific catalysis mechanisms and reaction rate information is generally incomplete.

Sources:

McBride, M.B, 1994, *Environmental Chemistry of Soils*, Oxford University Press, New York.

Nash, K.L., 2000, Thermally Unstable Complexants/Phosphate Mineralization of Actinides, Argonne National Laboratory, Argonne, IL. (Also available at: <http://www.ornl.gov/divisions/ctd/ESP/96tasks/thermal.htm>, posted April 14, 2000.)

Technique/technology # 8

Title: Reduction/Oxidation State Manipulation

Current maturity level: Reduction/oxidation reactions chemically convert hazardous contaminants (primarily metals) to less toxic and/or less mobile or inert compounds (CPEO 1998). Materials that can be injected into the subsurface to provide in situ oxidation include iron filings (zero-valent iron), and potassium permanganate grout. In situ

reduction/oxidation -manipulation creates a treatment zone in the subsurface for remediation of reduction/oxidation -sensitive contaminants in groundwater, including chromate, uranium, technetium, some chlorinated solvents, and some explosive compounds. Aquifer sediments can be chemically manipulated (reduced) so that they become the reactive media. Gaseous reduction is also being tested on chromate contaminated sites. Numerous other mechanisms are available for either reducing or oxidizing contaminants.

In situ hydrous pyrolysis/oxidation oxidizes dense nonaqueous phase liquid (DNAPLs) through the injection of steam and oxygen in contaminated soils (WPI 1998). This process is described under Steam Injection.

Range of Applicability: Process may have limited applicability at sites that contain a wide range of contaminants. The reason for this limitation is that a given reduction/oxidation reaction will limit the mobility of some contaminants while enhancing the mobility of others.

Needed R&D: Site-specific and contaminant-specific treatability studies are usually needed before implementation of reduction/oxidation manipulation.

Sources:

CPEO, 1998, *Soil Flushing*, project of the San Francisco Urban Institute at San Francisco State University, Center for Public Environmental Oversight, posted in the Technology Tree webpage at <http://www.cpeo.org/techtree/ttdescript/soilflus.htm>, created August 24, 1998.

WPI, 1998, *In Situ Redox Manipulation*, available at <http://www.lwpi.org/Initiatives/init/winter98/awards.htm>.

Technique/technology # 9

Title: In Situ Thermal Desorption

Current maturity level: ISTD uses electrical resistance heating elements through rods in a thermal well system. Applications to date have been up to 4.3 m (14-ft) deep (USACE 2000). The waste and contaminated soil are heated to temperatures between 315 and 538°C (600 and 1,000 F) to vaporize and destroy most organics. An aboveground vapor vacuum collection and treatment system destroys or absorbs the remaining organics and vents carbon dioxide and water. Achieving temperatures up to 427°C (800°F) may take 3 months or longer.

Range of Applicability: ISTD can effectively remove volatile and semi-volatile COCs as well as potentially destroy combustible organics depending on the temperatures and heating times maintained. While generally applied to organic contaminants, the process reportedly “has the potential to chemically stabilize plutonium and other radionuclides and metals and reduce their mobility” (Jorgensen et al. 1999).

Needed R&D:

Sources:

Jorgensen, D. K., D. F. Nickelson, R. A. Hyde, R. K. Farnsworth, J. J. Jessmore, 1999, *Evaluating In Situ Treatment Technologies for Buried Waste Remediation at the INEEL*, INEEL/CON-98-00879, Pre-print for publication in Waste Management 1999, February-March 1999.

USACE, 2000, *Hydrologic Evaluation of Landfill Performance, Version 3.07*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Technique/technology # 10

Title: Steam Injection

Current maturity level: Steam injection (a.k.a., dynamic underground stripping) targets organics, especially SVOCs and fuels, but can also be used to recover some inorganics. Steam is injected into the subsurface through injection wells. Vaporized contaminants, air, and water are recovered with vacuum extraction wells and treated.

Range of Applicability: The process has been widely used in the petroleum industry to enhance oil field production and its basic aspects are well understood. It has been used for remediation at depths between 1.5 and 36.5 m (5 and 120 ft). steam injection has also been used with bioremediation by injecting oxygen after the steam process to enhance microbial metabolism (CPEO 1998; DOE/EM 1997).

The process requires injected steam to contact the surfaces of contaminated soil particles and is therefore dependent on air conductivity of the subsurface. The process has limited applicability in fine-grained materials or in waste zones with irregular permeabilities.

Needed R&D: The potential for criticality inducement should be investigated when process will be used in source zones that contain fissionable materials.

Sources:

CPEO, 1998, *Soil Flushing*, project of the San Francisco Urban Institute at San Francisco State University, Center for Public Environmental Oversight, posted in the Technology Tree webpage at <http://www.cpeo.org/techtree/ttdescript/soilflus.htm>, created August 24, 1998.

DOE/EM, 1997, *In Situ Vitrification Fact Sheet*, Department of Energy and the Environmental Management Program available at <http://www.bechteljacobs.com/emef/newfacts/facts/insituvit.html>.

Technique/technology # 11

Title: Thermally Enhanced Vapor Extraction

Current maturity level: TEVES combines thermal desorption principles with soil vapor extraction. The subsurface is heated with an array of electrodes. Vapors are extracted via extraction wells, screened within the zone of contamination, and equipped with extraction pumps capable maintaining a vacuum within the zone of influence. Soil gases are recovered and directed through a process train which treats the gases prior to emission to the atmosphere as in traditional SVE (CPEO 1998).

Range of Applicability: Effective at reducing volatile and semi-volatile organic contaminants in the subsurface. Preferentially removes materials from high permeability zones in the subsurface,

but can be pulse-operated to allow diffusion to increase removal. The process is generally not effective for non-volatile organics, most inorganics, and radionuclides.

Needed R&D:

Sources:

CPEO, 1998, Soil Flushing, project of the San Francisco Urban Institute at San Francisco State University, Center for Public Environmental Oversight, posted in the Technology Tree webpage at <http://www.cpeo.org/techtree/ttdescript/soilflus.htm>, created August 24, 1998.

Technique/technology # 12

Title: Radio Frequency Heating

Current maturity level: RFH uses radio frequency energy applied through exciter electrodes to heat the subsurface and volatilize certain organic contaminants, especially VOCs and SVOCs. Closely spaced electrodes are required, as each heating zone has an approximate 1 m (3 ft) radius of influence. Operating temperatures, selected for the target contaminants, are generally on the order of 150°C (302°F), but can reach up to 1330°C (2426°F) at exciter electrodes (EPA 1995). Soil gases are recovered with vacuum extraction and directed through a process train that treats the gases.

Range of Applicability: The use of RFH process is limited to the vadose zone, and is not effective near or below the water table.

Needed R&D:

Sources:

EPA, 1995, IITRI Radio Frequency Heating Technology – Innovative Technology Evaluation Report, EPA/540/R-94/527, Superfund Innovative Technology Evaluation (SITE), Environmental Protection Agency, Washington D.C., June 1995.

Technique/technology # 13

Title: In Situ Vittrification

Current maturity level: ISV uses electrical heat to melt soil and waste into a mass of fused glass similar to obsidian. Electrodes inserted into the ground in a square array transmit current to the soil until it melts, volatilizing VOCs and SVOC and immobilizing other COCs in the process. As the electrodes sink through the molten material, the melt zone advances downward. Off-gases from the process are collected and treated. Planar ISV provides preferential pathways for the escape of vapors between the two planar melts until they fuse together. A 3 m (10 ft) thick cover of unconsolidated materials is maintained over the melt zone in the application of planar ISV. This zone protects equipment and personnel at the surface from exposure to heat and molten soil expulsions. Melts up to 13.7 m (45 ft) in diameter have been produced. Melts can be overlapped to treat a large site.

Range of Applicability: The attainable depth of ISV has been increasing as the technology improves. Currently, the deepest ISV melt has penetrated to 8 m (26 ft) below the ground surface (MSE Technology Applications 1999).

Needed R&D: More information about the differentiation of metals within the melt zone is needed. This differentiation has the potential for limiting the long term effectiveness of ISV melts at some sites.

Sources:

MSE Technology Applications, 1999, Final Report – Cold Demonstration of Nontraditional In Situ Vitrification at the Los Alamos National Laboratory, ECCP-11, prepared for the Department of Energy, Los Alamos National Laboratory, Los Alamos, New Mexico, November 1999.

Technique/technology # 14

Title: Electro Kinetic Remediation

Current maturity level: Electrokinetic remediation removes metal and radionuclide contaminants from the soil by applying a low-level direct current to the contaminated zone with electrodes placed in the ground. ER uses electromigration of ionic species and electro-osmosis. The process works in low-permeability soils, imposing a high degree of control of flow direction as ions move along electric field lines determined by electrode placement. Contaminants are extracted from the circulating electrolytes inside the electrodes.

Range of Applicability: Effectiveness depends on interfering chemicals and adequate current density (USACE 2000). May be effective in fine-grained soils where most extraction methods are least efficient (EPA 1999). Field scale test results for US Army were disappointing (USACE 2000).

Needed R&D:

Sources:

EPA, 1999, *SITE Technology Profile Demonstration Program*, EPA/540/R-99/500a, Superfund Innovative Technology Evaluation (SITE), Environmental Protection Agency, Washington D.C., February 1999.

USACE, 2000, *Hydrologic Evaluation of Landfill Performance*, Version 3.07, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Technique/technology # 15

Title: In Situ Anaerobic Bioremediation

Current maturity level: In situ anaerobic biological degradation is generally used for particular contaminants that are not readily degraded by aerobic treatment, such as highly substituted aliphatics and highly chlorinated aromatics, including tetrachloroethene, PCBs, and hexachlorobenzene. A typical anaerobic system injects an electron donor substrate into the subsurface (EPA 1999). Airflow into the treatment zone may need to be controlled so that anoxic conditions are maintained.

Range of Applicability: . May not be effective in low-permeability conditions or in containerized waste. Not well suited to fine-grained soils (CPEO 1998). Process also may have limited utility at large sites due to the need to maintain anoxic condition

Needed R&D:

Sources:

EPA, 1999, SITE Technology Profile Demonstration Program, EPA/540/R-99/500a, Superfund Innovative Technology Evaluation (SITE), Environmental Protection Agency, Washington D.C., February 1999.

Technique/technology # 16

Title: Aerobic Bioremediation

Current maturity level: In situ aerobic biological treatment results in the transformation or mineralization of organic contaminants caused by the activities of naturally occurring or specifically engineered microorganisms. Depending on the microbial population and dominant processes, these activities can either break down organic contaminants or mobilize inorganic contaminants for removal. Microbes are affected by temperature, moisture, nutrients, and oxygen, which can be optimized to maximize treatment. Also, specific microbial organisms can be injected to target a particular contaminant. A typical system injects oxygen, or other nutrients, to enhance the growth of microbial populations. Aerobic degradation involves higher metabolic rates, and is generally preferred over anaerobic systems. Process options may be combined to address particular contaminants that would benefit from first anaerobic, then aerobic, degradation (EPA 1999).

Range of Applicability: Some chemicals may be degraded to more toxic products (e.g., trichlorethene to vinyl chloride) (CPEO 1998). May not be effective in low-permeability conditions or in containerized waste. May be difficult to control in fine-grained soils.

Needed R&D:

Sources:

CPEO, 1998, *Soil Flushing*, project of the San Francisco Urban Institute at San Francisco State University, Center for Public Environmental Oversight, posted in the Technology Tree webpage at <http://www.cpeo.org/techtree/ttdescript/soilflus.htm>.

Technology Pathway Summary (Form B)

Capability to be improved: 1.4a Engineer Biogeochemical Environment (source)

Associated Target(s): 1.4a Deploy alternate technologies that detoxify or immobilize risk-driving contaminants at the source.

The traditional waterfall model is the natural way of managing the development of something innovative and complex. In using the waterfall model the project proceeds according to clearly defined phases; a preceding phase must be completed before the next starts; phase completion is judged by the outcome of the phase matching the requirements defined by the previous phase.

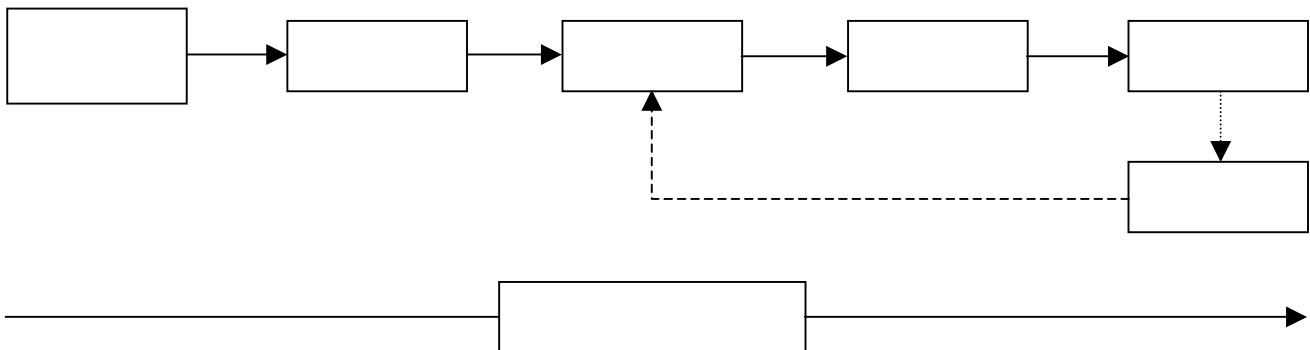
The phases of the traditional model are:

1. Concept
2. Feasibility analysis
3. User Definition of System Requirements
4. Developer Definition of System Requirements
5. High-Level Design
6. Detailed Design
7. Prototype development
8. Integration and Test
9. System Test
10. Acceptance Test
11. Operations
12. Maintenance.

To achieve targets 1.4a and 1.4b, the LTS CC&C working group consolidated the traditional waterfall model into the following technology development pathway:

1. Situation/Requirements Analysis (Pre-lab/field research). Review and status knowledge and needs. (1 – 6 months)
 - a. State-of-science literature review.
 - b. Existing system / performance data
 - c. Emerging technology / preliminary data
 - d. Field needs (user)
 - e. Regulator and stakeholder needs (step 1 of ongoing consensus building)
 - f. Map existings and emergings (items a-c) to needs (items d-e) and identify gaps.
2. Basic Research. Proof-of concept: laboratory and theory. (6 – 24 months)
 - a. Generic treatability studies (e.g., effectiveness and reasonable ranges for reagent and delivery mode)
 - b. Predictive models and tools (e.g., simulation of fate and transport, protocols for applied studies)
 - c. Regulator and stakeholder input.
3. Site-specific Research. Proof-of-application: laboratory and theory. (6 – 12 months)

- a. Site-specific treatability studies (considering contaminants, matrix, environmental setting ... for site-specific system requirements)
 - b. Predictive models and tools (e.g., site-specific fate and transport simulation over time; considering expected change, cost and other performance requirements, indicators, surrogates, and analogs)
 - c. Regulator and stakeholder input – interaction.
4. Site Demonstration. Pilot testing. (6 – 12 months)
 - a. Field tests (scale-up from lab/bench-scale trials, calibration studies)
 - b. Predictive models and tools (performance standards, optimization studies with predictions of performance over time, preliminary specifications)
 - c. Regulator and stakeholder input – interaction.
5. Site Deployment. Scale-up and deployment. (6 months)
 - a. Engineering analysis, cost analysis, commercialization and vendor selection / full-scale implementation
 - b. Predictive models and tools (to optimize final system design, incorporating smart monitoring and maintenance that promote elements of the natural system and considering full life-cycle costs)
 - c. Regulatory approval (e.g., license, permit), regulator and stakeholder input – interface
6. Post-Deployment. Validation → Iterative system refinement / replacement. (3 months – design life)
 - a. Evaluation of system performance / monitoring data
 - b. Predictive models and tools (time series / trend analyses)
 - c. Regulator and stakeholder input – interaction
 - d. Info management and overall process system feedback loop (of items a-c).



1. Limit Contaminant Toxicity and Mobility

Technical Approaches (Form A)

Capability to be improved: 1.4b Engineer [Thermo]biogeochemical Environment (ground water)

Associated Target(s): 1.4b Deploy alternate technologies that reduce the volume of contaminated ground water that would otherwise have been pumped and/or treated.

Overall Need: There are 176 groundwater plumes across the DOE complex. Baseline cleanup/closure plans and life-cycle cost estimates for many of these plumes assume that alternatives to pump and treat will be deployed. However, because needed science and technology does not yet exist to implement alternative technologies for many of these plumes, long-term pump-and-treat still must be assumed to be the default technology for these plumes. Deployment of alternatives to pump and treat would allow DOE to realize substantial cost savings. Also, at several DOE sites it is expected or planned that contaminated water will be collected (for example, in french drains) over the long term for ex situ treatment. Engineering of the thermobiogeochemical environment could reduce the volume of water requiring treatment at these sites.

Technique/technology # 1

Title: [Phytoremediation; phytotechnology to manipulate plume hydraulics](#)

Current maturity level: Ranges from demonstrated/accepted technology (for a limited range of applications) to investigational technology (for other applications).

Range of Applicability: All applications are limited to locations where contaminants or contaminated water are present in the shallow subsurface (within depths of plant roots). Phytoremediation [involves the use of plants and plant physiological processes \(primarily in the rhizosphere\) to destroy, detoxify, or immobilize contaminants](#). Phytoremediation has been successfully demonstrated, and thus is potentially applicable, primarily for nitrates (including explosives, in soil or in plumes) and other nutrient-rich plumes and secondarily for organic plumes. Phytotechnology to manipulate plume hydraulics is potentially applicable primarily to plumes in shallow alluvial aquifers (on stream terraces and floodplains) in subhumid-to-arid locations (where plant water utilization can substantially affect water flux).

Needed R&D:

- Site-specific treatability studies, including plant screening and selection for specific applications, water balance studies, and measurements of uptake/transformation rates.
- Improved understanding of rhizosphere transformation processes and contaminant fate (needed to build confidence in long-term effectiveness and safety of phytoremediation)

Sources:

<http://www.rtdf.org/public/phyto/default.htm> - Phytoremediation of Organics Action Team of Remediation Technologies Development Forum

<http://www.wes.army.mil/el/phyto/> - Phytoremediation Research at U.S. Army Corps of Engineers Waterways Experiment Station Environmental Laboratory

http://clu_in.org/products/phytotce.htm - Phytoremediation of TCE in Groundwater using *Populus*, prepared for the U.S. EPA Technology Innovation Office by Jonathan Chappell. February 1998.

<http://www.gwrtac.org/html/topics/phytozem.htm> - Technology Evaluation Report: Phytoremediation, Ground-Water Remediation Technologies Analysis Center, October 1997

Technique/technology # 2

Title: Enhanced bioremediation.

Current maturity level: Bioremediation involves the use of microbial processes to destroy, detoxify, or immobilize contaminants. This occurs naturally to some extent, but enhanced bioremediation involves manipulation of natural systems to facilitate or accelerate the natural processes. Demonstrated/accepted technology for organics and nutrients. Investigational technology for metals and radionuclides.

Range of Applicability: Potentially applicable to almost all plumes. However, plume depth and geohydrologic complexity place practical limits on application for all contaminant types, not all metals and radionuclides are treatable with bioremediation, and complex mixtures of contaminants may not be treatable.

Needed R&D:

- Demonstrate applications for metals and radionuclides.
- Develop improved capabilities to deliver agents to stimulate bioremediation (such microorganisms, nutrients, air, carbon sources, and electron donors and acceptors), more efficiently, at greater depths, and in more complex geologic settings.
- Treatability studies needed to apply effectively and optimize application at specific sites.
- Confidence-building: Develop improved prediction and understanding of system performance in order to achieve regulatory and stakeholder acceptance of these technologies. For metals and radionuclides, develop an improved understanding of biological transformations of DOE contaminants and of the long-term stability of the apparently stable/immobile forms produced by bioremediation. For chlorinated organics, develop an improved understanding of the nature and environmental fate of breakdown products. For all applications, develop improved understanding of long-term behavior and performance of bioremediation systems, including biofouling and other effects on hydraulic and geochemical characteristics of flow media.

Sources:

http://www.itrcweb.org/isb_6.pdf - Technical and Regulatory Requirements for Enhanced In Situ Bioremediation of Chlorinated Solvents in Groundwater, December 1998, Interstate Technology and Regulatory Cooperation Workgroup In Situ Bioremediation Subgroup

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. Use of Bioremediation at Superfund Sites. EPA-542-R-01-019, September 2001.

<http://www.lbl.gov/NABIR/generalinfo/primer/primer.html> – Bioremediation of Metals and Radionuclides - What it is and how it works. Natural and Accelerated Bioremediation Research program (NABIR) of the Office of Biological and Environmental Research of the DOE Office of Science.

<http://www.lbl.gov/NABIR/researchprogram/researchtopics/index.html> - Natural and Accelerated Bioremediation Research program research topics

Note: NABIR projects a 7-to-10-year time frame to field demonstration of strategies to accelerate intrinsic processes for immobilization of metals and radionuclides. See

<http://www.lbl.gov/NABIR/researchprogram/researchtopics/biotransformation.html>

http://www.lbl.gov/NABIR/generalinfo/workshop_reports/Final_Workshop.pdf – Workshop Report: “Combined Chemical and Microbiological Approaches to Remediating Metal and Radionuclide Contaminants” 1999.

[Related techniques/technologies:](#)

CC&C 1.4a, Tech. 15: In Situ Anaerobic Bioremediation

CC&C 1.4a, Tech 16: In Situ Aerobic Bioremediation

Technique/technology # 3

Title: Subsurface introduction of chemical reactants, including passive reactive barriers.

Current maturity level: Being field-demonstrated and/or used commercially in the form of passive-reactive barriers for treatment of plumes containing nutrients, organics, and chromate. Other applications potentially applicable to DOE, including (1) injection of chemical reactants directly into plumes and (2) use of passive reactive barriers for metals and radionuclides, are in laboratory investigation or early stages of field investigation. [The feasibility of this technology and the choice of chemical reactants are highly contaminant-specific. Many applications involve introduction of oxidizing or reducing agents to change the chemical speciation, and thus the solubility, of inorganic contaminants or to induce the decomposition of organic contaminants. Other applications and potential applications involve \(1\) the introduction of neutralizing agents to control contaminant solubility by changing the pH of the plume and \(2\) the introduction or emplacement of reactive media \(such as zeolite or apatite\) to capture contaminants through ion exchange or similar reactions.](#)

Range of Applicability: Potentially applicable to many plumes. Technical constraints currently impede use for deep plumes and for plumes in low-permeability and complex/heterogeneous geologic media.

Needed R&D:

- Investigate/develop passive-reactive barrier materials for use with metals, radionuclides, and plumes that include mixtures of contaminants.
- Investigate/develop the potential to introduce chemical reactants in the form of gases and colloids to overcome constraints associated with various complex geologic settings and with implementing remediation in the presence of buried utilities and other facility infrastructure.
- Demonstrate capabilities for in situ placement of chemical reactants (in all settings).

- Develop and demonstrate techniques for deep emplacement (and verification of deep emplacement) of passive reactive barriers.
- Develop improved understanding of phenomena affecting passive-reactive barrier performance over the short and long term, including reaction kinetics, role of microbial interactions in contaminant degradation, and fundamental understanding of processes that lead to degradation or clogging of barrier media, including biofouling, corrosion, and precipitation of reaction products.
- Site-specific treatability studies.
- Develop improved methods for monitoring system effectiveness and maintaining system performance.

Sources:

http://www.itrcweb.org/ISCO_1.pdf - Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater, Interstate Technology and Regulatory Cooperation Work Group In Situ Chemical Oxidation Work Team, June 2001.

<http://www.rtdf.org/public/permbarr/default.htm> - Permeable Reactive Barriers Action Team of the Remediation Technologies Development Forum

<http://www.rtdf.org/public/permbarr/minutes/061201.htm> - Summary of the Remediation Technologies Development Forum Permeable Reactive Barriers Action Team Meeting, June 12, 2001. (Summaries and discussions of ongoing research and findings, including investigations of emplacement techniques and barrier performance, investigations of new barrier materials, a permeable reactive barrier incorporating zeolite to remove strontium, and use of ultrasound to reduce clogging in an in-place metallic iron barrier.)

<http://207.86.51.66/download/rtdf/prb/reactbar.pdf> - Permeable Reactive Barrier Technologies for Contaminant Remediation, EPA/600/R-98/125. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Research and Development.

http://www.lbl.gov/NABIR/generalinfo/workshop_reports/Final_Workshop.pdf – Workshop Report: “Combined Chemical and Microbiological Approaches to Remediating Metal and Radionuclide Contaminants” 1999.

<http://www.powellassociates.com/sciserv/Perm.barrier.main.html> - “Permeable Reactive Barriers Notebook”

LTS database references (Long Term Stewardship Technology Analysis of the Office of Science and Technology Profile, September 2001):

Surface Altered Zeolites as a Permeable Barrier (page 159), Verification of Subsurface Barriers/Moisture Detection (page 178), Subsurface Barrier Emplacement (page 191), In Situ Redox Manipulation (page 192), Permeable Reactive Treatment (PeRT) Wall for Rads and Metals (page 207), Fracture Permeable Reactive Barrier (page 224), Reactive Barrier Performance: DNAPL (page 252)

Related techniques/technologies:

CC&C 1.4a, Tech. 8: Reduction/Oxidation State Manipulation

CC&C 1.4b, Tech 2: Enhanced bioremediation (*related because microbial processes can contribute to, interfere with, and/or be adversely affected by measures to engineer chemical reactions in the environment*)

Technique/technology # 4

Title: Engineered Wetlands.

Current maturity level: Engineered wetlands can destroy, detoxify, or immobilize contaminants in water through a combination of processes including physical sedimentation (of suspended material or contaminants precipitated by other chemical reactions occurring in the wetland system), microbial processes, plant physiological processes, chemical precipitation, and adsorption/ion exchange in wetland soils. This is demonstrated/accepted technology for treating stormwater runoff, acidic mining wastes (typically containing heavy metals whose solubility is controlled by pH), some organics, and small flows of sanitary wastewater. Investigational in other applications. The feasibility and implementation of this technology are highly contaminant- and site-specific.

Range of Applicability: Shallow drains and other locations where contaminated groundwater discharges to the surface. *Also potentially applicable (as a retrofit) under capability 5.1, as a longer-lived water treatment technology to reduce required maintenance interventions in installed contaminant control systems that include water collection and treatment.*

Needed R&D:

- Determine potential applicability to radionuclides and other DOE contaminants, both generically and for specific waste sources and sites (site-specific treatability studies needed before implementation).
- Develop efficient methods for monitoring system performance.
- Develop improved methods for maintaining system performance (*capability 5.1*)

Sources:

http://www.clu.in.org/download/remed/constructed_wetlands.pdf - Constructed Wetlands: Passive Systems for Wastewater Treatment, Technology Status Report prepared for the US EPA Technology Innovation Office, August 2001

Related techniques/technologies:

CC&C 1.4b, Tech 1: Phytoremediation

CC&C 1.4b, Tech 2: Enhanced bioremediation

Technique/technology # 5

Title: Air Sparging and Soil Vapor Extraction

Current maturity level: Demonstrated / accepted for organics.

Range of Applicability: Organic plumes in relatively permeable settings.

Needed R&D:

- Determine risk and regulatory acceptability of air releases
- Treatability studies needed to optimize application at specific sites.

Sources:

<http://www.gwrtac.org/html/topics/soilvapor.htm> - Soil Vapor Extraction / Dual Phase Extraction, Ground_Water Remediation Technologies Analysis Center, October, 1996

<http://www.gwrtac.org/html/topics/airsparg.htm> - Air Sparging _ Technology Overview, Ground_Water Remediation Technologies Analysis Center, October, 1996

Related techniques/technologies:

CC&C 1.4a: Tech # 1, Soil Vapor Extraction – This technology is applicable to control of organic contaminants at the source or in the environment.

Technique/technology # 6

Title: Dynamic Stripping for DNAPLs.

Current maturity level: Demonstrated at field scale.

Range of Applicability: Broad range of DNAPL contaminants, limited to vadose zone.

Needed R&D: “Confidence building” activities to move from state-of-art to state-of-practice.

Sources:

<http://www.rtdf.org/public/flushing/default.htm> – In Situ Flushing Action Team of the Remediation Technologies Development Forum

Related techniques/technologies:

CC&C 1.4a, Tech. 10: Steam Injection

Technology Pathway Summary (Form B)

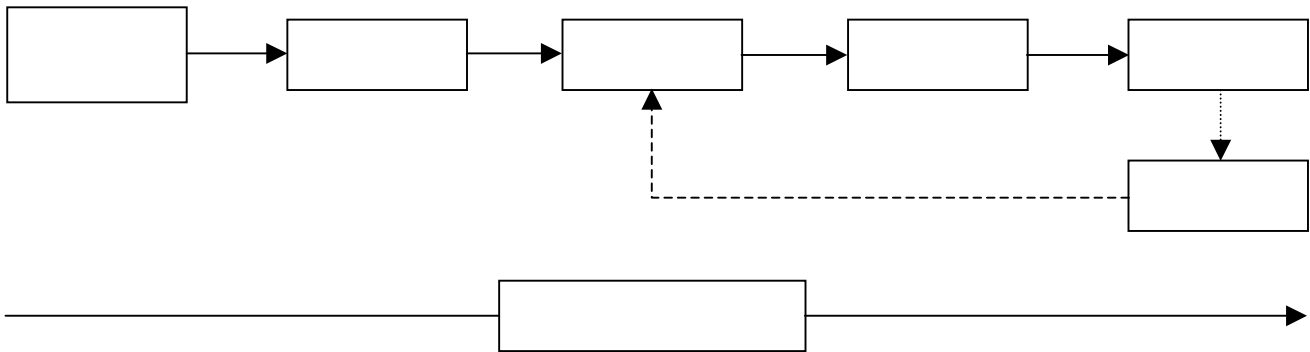
Capability to be improved: 1.4b Engineer Biogeochemical Environment (ground water

Associated Target(s): 1.4b Deploy alternate technologies that reduce the volume of contaminated ground water that would otherwise have been pumped and/or treated.

To achieve targets 1.4a and 1.4b, the LTS CC&C working group consolidated the traditional waterfall model into the following technology development pathway:

1. Situation/Requirements Analysis (Pre-lab/field research). Review and status knowledge and needs. (1 – 6 months)
 - a. State-of-science literature review.
 - b. Existing system / performance data
 - c. Emerging technology / preliminary data
 - d. Field needs (user)
 - e. Regulator and stakeholder needs (step 1 of ongoing consensus building)
 - f. Map existings and emergings (items a-c) to needs (items d-e) and identify gaps.
2. Basic Research. Proof-of concept: laboratory and theory. (6 – 24 months)
 - a. Generic treatability studies (e.g., effectiveness and reasonable ranges for reagent and delivery mode)
 - b. Predictive models and tools (e.g., simulation of fate and transport, protocols for applied studies)
 - c. Regulator and stakeholder input.
3. Site-specific Research. Proof-of-application: laboratory and theory. (6 – 12 months)
 - a. Site-specific treatability studies (considering contaminants, matrix, environmental setting ... for site-specific system requirements)
 - b. Predictive models and tools (e.g., site-specific fate and transport simulation over time; considering expected change, cost and other performance requirements, indicators, surrogates, and analogs)
 - c. Regulator and stakeholder input – interaction.
4. Site Demonstration. Pilot testing. (6 – 12 months)
 - a. Field tests (scale-up from lab/bench-scale trials, calibration studies)
 - b. Predictive models and tools (performance standards, optimization studies with predictions of performance over time, preliminary specifications)
 - c. Regulator and stakeholder input – interaction.
5. Site Deployment. Scale-up and deployment. (6 months)
 - a. Engineering analysis, cost analysis, commercialization and vendor selection / full-scale implementation

- b. Predictive models and tools (to optimize final system design, incorporating smart monitoring and maintenance that promote elements of the natural system and considering full life-cycle costs)
 - c. Regulatory approval (e.g., license, permit), regulator and stakeholder input – interface
6. Post-Deployment. Validation → Iterative system refinement / replacement. (3 months – design life)
- a. Evaluation of system performance / monitoring data
 - b. Predictive models and tools (time series / trend analyses)
 - c. Regulator and stakeholder input – interaction
 - d. Info management and overall process system feedback loop (of items a-c).



Technology Pathway Summary (Form B)

Capability to be improved: 1.4b Engineer Biogeochemical Environment (ground water

Associated Target(s): 1.4b Deploy alternate technologies that reduce the volume of contaminated ground water that would otherwise have been pumped and/or treated.

Technology-specific pathways

Technique/technology 1 - Phytoremediation

Steps 1 and 2 are largely complete, and therefore are omitted.

3-4. Site specific treatability studies and site demonstration (Conduct in parallel; 12-24 months)

Prerequisite: Contaminant types and geohydrologic setting are evaluated and found to be generically suitable for this technology.

- a. Identify and screen plant species for potential application of phytotechnologies at site of interest.
- b. Perform water balance studies.
- c. Conduct bench-scale and plot studies of contaminant uptake and transformation under site conditions.
- d. Model and predict site-specific performance.
- e. Evaluate whether results and predictions are acceptable; obtain regulator and stakeholder input.

5. Site deployment

Prerequisite: Successful bench- and field-scale testing; regulator/stakeholder buy-in.

- a. Design full-scale implementation (engineering and cost analyses) and obtain regulator approval.
- b. Implement

6. Post-deployment monitoring with feedback into predictive models and design

7. Regulator and stakeholder consensus building -- needed throughout

Technique/technology 2 - Enhanced bioremediation

Different development pathways exist for applications to different contaminant types and geohydrologic settings:

- For metals and radionuclides, follow full 7-step sequence.
- For organic and nutrient plumes at shallow depth in relatively permeable porous media, begin with step 3. (Steps 1 and 2 are largely complete, although technical enhancements and confidence-building steps may be needed to support implementation.)
- For deep plumes and plumes in complex geohydrologic settings, follow full 7-step sequence.

Technique/technology 3 - Subsurface introduction of chemical reactants

This technique/technology group includes several different specific technologies, with slightly different development pathways:

- Passive reactive barrier technology using metallic iron to treat organic solvent plumes at shallow to moderate depth – Pathway begins with step 3. (Steps 1 and 2 are largely complete, although technical enhancements, improved conceptual understanding and predictive capabilities, and related confidence-building may be needed to support implementation.)
- Passive reactive barrier technology for use with metals, radionuclides, and plumes that contain mixtures of contaminants – Pathway begins with steps 1 and 2. Step 1, requirements analysis, is largely complete. Step 2 (proof of concept) could be combined with step 3 (site-specific treatability and implementability) because most needs are highly site-specific and successful testing or demonstration for a particular site would help provide generic proof of concept.
- Passive reactor barriers for plumes deeper than current emplacement technology can reach – Pathway begins with step 2. Needs are well understood, so step 1 is not needed.
- Introduction of chemical reactions directly into plumes – Pathway follows full 7-step sequence. However, steps 2 and 3 could be combined because most needs are highly site-specific (necessitating site-specific treatability/implementability studies at an early stage) and successful testing or demonstration for a particular site would help provide generic proof of concept.

Technique/technology 4 – Engineered wetlands

Development pathway begins with step 3, site-specific treatability/implementability. For applications that have not been demonstrated generically, findings of site-specific investigations would help determine generic applicability.

Technique/technology 5 – Air sparging and soil vapor extraction

Focused technology development needs exist in two areas, with distinct development pathways:

- To determine risk and regulatory acceptability of air releases, start with step 1 (state-of-the-science literature review, evaluation of data on existing system performance, and identification of regulator and stakeholder needs and concerns). Continue with step 2 (simulation of fate and transport, and interaction with regulators and stakeholders). Based on information needs identified in these steps, conduct post-deployment monitoring (step 6) at sites where this technology has been deployed, and use findings to improve products of step 2, support step 7 (confidence-building), and provide input to actual deployments.
- For site-specific deployment, step 3 (site-specific research) is a prerequisite. Site-specific treatability investigations would focus on evaluating and modeling site matrix physical (hydrogeologic) attributes, contaminant physical properties, and physicochemical interactions between contaminants and site matrix. Duration of step 3 is estimated to be 6 months. Completion of the risk and regulatory acceptability development sequence also may be a prerequisite for stakeholder and regulatory acceptance at some sites.

Technique/technology 6 – Dynamic stripping for DNAPLs

A focused technology development effort is needed to build confidence in the effectiveness of this technology. This can best be achieved in part by site-specific deployment (step 3, followed by steps 4-6 and in parallel with step 7).

2. Limit Intrusion, Transport, Release, and Exposure

Technical Approaches (Form A)

Capability to be improved: 2.2a Design, build, and operate alternative containment systems (covers).

Associated Target(s): 2.2a Deploy *cover systems* that mimic natural processes and accommodate environmental change.

Cover designs are needed that will contain buried wastes for hundreds to thousands of years, and do so while natural processes are acting to mobilize contaminants. This is an unprecedented engineering challenge. Current design approaches, which attempt to engineer barriers that block contaminant release processes such as water flux, erosion and biointrusion, have failed in the short term—the barriers degrade with time. DOE needs an alternative approach for designing, building and operating sustainable covers that mimic favorable elements of natural landscapes, which have already passed the test of time. This capability and target are closely linked to Capability and Target 4.1, “develop a toolbox . . . (e.g., models, natural analogs, guidance, etc.) . . . to improve planning, decision making, designing, monitoring, maintenance . . .”

Technique/technology # 1

Title: Biointrusion Barriers.

Barriers are needed that prevent burrowing and tunneling animals, and deep-rooted plants, from contacting and mobilizing subsurface contaminants or from disrupting critical cover layers. Physical and chemical barriers (e.g. subsurface rock or time-release herbicide layers) are necessary in some designs. Ideally, however, after thorough characterization of the local ecology, covers can be designed to accommodate plant and animal habitat without the need for physical or chemical barriers.

Current maturity level: Design and construction of physical and chemical biointrusion barriers are well-documented and demonstrated. Some have been deployed. The prospect of accommodating plant and animal habitat in a design must be evaluated on a site-by-site basis.

Range of Applicability: In the long term, ecological development is inevitable on all covers.

Needed R&D: (1) Evaluate the performance of existing deployments. (2) Develop guidance or provide expert technical assistance to walk a designer through baseline ecological evaluations that are needed to design a cover that prevents biointrusion.

Sources:

Anderson, J.E., and A.D. Forman, 2002. The Protective Cap/Biobarrier Experiment: A Study of Alternative Evapotranspiration Caps for the Idaho National Engineering and Environmental Laboratory. STOLLER-ESER-46, S.M. Stoller Corporation, Idaho Falls, ID.

Bowerman, A.G., and E.D. Redente, 1998. Biointrusion of protective barriers at hazardous waste sites. J. Environ. Qual. 27 :625-632.

Hakanson, T.E., L.J. Lane, and E.P. Springer, 1992. Biotic and abiotic processes. In: C.C. Reith and B.M. Thompson (eds.). Deserts as Dumps? The Disposal of Hazardous Materials in Arid Ecosystems (pp. 101-146).

Link, S.O., L.L. Cadwell, K.L. Petersen, M.R. Sackschewsky, and D.S. Landeen, 1995. The Role of Plants and Animals in Isolation Barriers at Hanford, Washington. PNL-10788, Pacific Northwest National Laboratory, Richland, WA.

Suter, G.W., R.J. Luxmoore, and E.D. Smith, 1993. Compacted soil barriers at abandoned landfill sites are likely to fail in the long term. J. Environ. Qual. 22:217-226.

Waugh, W.J., and G.N. Richardson, 1997. Ecology, Design, and Long-Term Performance of Surface Barriers: Applications at a Uranium Mill Tailings Site, pp. 36-49. In: Barrier Technologies for Environmental Management, National Research Council, National Academy Press, Washington, D.C.

Technique/technology # 2

Title: Rock / Soil Armoring (e.g., mimic desert pavements).

Vegetation may be too sparse to stabilize soil covers in arid and semiarid regions, especially on steeper side slopes. UMTRA design guidance specifies highly durable rock on slopes as a means of controlling erosion. However, by reducing evaporation and increasing soil water storage, rock layers increase water infiltration, which can lead to root intrusion and an increase in the hydraulic conductivity of underlying soil layers. Layers of rock and soil mixed together can control erosion and also enhance plant growth and water extraction (evapotranspiration), much like desert pavements and vegetated slide rock. By allowing safe placement of waste under side slopes, covers armored with rock, soil and plants will have significantly smaller footprints and cost less.

Current maturity level: Effects of gravel admixture layers on soil loss, plant growth and soil water balance have been demonstrated and designs have been deployed at a few sites. Analogs of the stability of thick admixture layers of rock, soil, and vegetation for use on side slopes have been investigated, but engineered designs have not been attempted.

Range of Applicability: Arid and semiarid sites, especially sites requiring sloped covers.

Needed R&D: (1) Evaluate the stability, soil water balance, and ecology of existing deployments having gravel admixture designs on the top slope. (2) Design (mimic) and test the performance (soil water balance and stability) of vegetated rocky slopes. (3) Develop guidance or provide expert technical assistance to help design rock/soil layers.

Sources:

Sackschewsky, M.R., C.J. Kemp, S.O. Link, and W.J. Waugh, 1995. Soil water balance changes in engineered soil surfaces. Journal of Environmental Quality 24:352-359.

Smith, G.M., W.J. Waugh, and M.K. Kastens, 1997. Analog of the long-term performance of vegetated rocky slopes for landfill covers, pp. 291-300. In: Tailings and Mine Waste '97, A.A. Balkema, Rotterdam.

Waugh W.J., M.E. Thiede, and D.J. Bates, 1994. Plant cover and water balance in gravel admixtures at an arid waste-burial site. Journal of Environmental Quality 23:676-685.

Winkel, V.K., B.A. Roundy, and J.R. Cox, 1991. Influence of seed microsite characteristics on grass seedling emergence. Journal of Range Management 44:210-214.

Technique/technology # 3

Title: Water balance designs (evapotranspiration covers, capillary barriers, water shedding covers).

Arid and semiarid ecosystems often return all precipitation to the atmosphere via evapotranspiration. Cover designs can mimic these ecosystems. Recharge is limited if designs use thick, fine-textured soil covers that store precipitation in the root zone where it is seasonally removed by evapotranspiration. The water-storage capacity is increased when the fine-textured soil “sponge” is placed over a coarse sand or gravel layer creating a capillary barrier. Unless the water content of the soil layer exceeds its storage capacity, downward water movement is inconsequential. At humid sites, where precipitation exceeds evapotranspiration, recharge can be prevented by shedding water to the perimeter of the cover. Then evapotranspiration can remove the lesser amounts of water that infiltrate the soil.

Current maturity level: Evapotranspiration covers with and without capillary barriers and water shedding covers have been demonstrated in large lysimeters (field tests), and a few have been deployed. Evaluations of long-term performance using analogs is underway.

Range of Applicability: Arid, semiarid, and humid sites requiring long-term covers.

Needed R&D: Many water balance cover prototypes and demonstrations have been installed, and there have been a few deployments, but few have been monitored long enough for vegetation to mature. Need to (1) resume performance evaluations of field installations with mature vegetation, (2) test a water-shedding design made of natural materials at humid sites, (3) develop guidance for projecting long-term performance of cover systems that links natural analogs with field tests and probabilistic modeling, and (4) Develop long-lasting monitoring tools that target early-warning of potential changes in system performance; methods for remote sensing (large-scale measurement) of natural indicators of change (e.g. phytomonitoring) are needed.

Sources:

Anderson, J.E., and A.D. Forman, 2002. The Protective Cap/Biobarrier Experiment: A Study of Alternative Evapotranspiration Caps for the Idaho National Engineering and Environmental Laboratory. STOLLER-ESER-46, S.M. Stoller Corporation, Idaho Falls, ID.

Dwyer, S.F., 1998. Alternative covers pass the test. Civil Engineering, September, pp. 50-52.

Gee, G.W. and S.W. Tyler (eds.), 1994. “Symposium: Recharge in Arid and Semiarid Regions,” Soil Science Society of America Journal 58:5–72.

Link, S.O., N.R. Wing, and G.W. Gee, 1994. “The Development of a Permanent Isolation Barrier for Buried Wastes in Cool Deserts: Hanford, Washington,” Journal of Arid Land Studies 4:215–224.

O’Donnell, E., R.W. Ridky, and R.K. Schultz, 1994. Control of Water Infiltration into Near-Surface, Low-Level Waste-Disposal Units in Humid Regions. pp. 295-324. In G.W. Gee and N.R. Wing (eds.), In-Situ Remediation: Scientific Basis for Current and Future Technologies. Battelle Press, Columbus, OH.

Ward, A. L., and G. W. Gee. 1997. "Performance Evaluation of a Field-Scale Surface Barrier". J. Environ. Qual. 26:694-705.

Waugh, W.J., 2002. Monticello Field Lysimetry: Design and Monitoring of an Alternative Cover. Proceedings of the Waste Management 2002 Symposium, University of Arizona, Tucson, Arizona, February 25-28, 2002.

Waugh, W.J., K.L. Petersen, S.O. Link, B.N. Bjornstad, and G.W. Gee, 1994. Natural Analogs of the Long-term Performance of Engineered Covers, pp. 379-409. In G.W. Gee and N.R. Wing (eds.), In-Situ Remediation: Scientific Basis for Current and Future Technologies. Battelle Press, Columbus, OH.

Technique/technology # 4

Title: Geomorphological Geometry

The design and construction of a long-term cover can be viewed as the formation of a new geomorphic landform with a new soil parent material. Pedogenesis and surficial geomorphic processes will inevitably alter the original engineered character of the cover, possibly impacting both the short- and long-term performance of the cover. Sustainable designs will mimic geologically stable surfaces, for example, by designing drainage networks into a cover based on geologic conditions similar to the landfill site.

Current maturity level: Many deployed covers have drainages to channel runoff water away from disposal cells. The UMTRA program has investigated analogs of stable slopes, and development of guidance for characterizing natural analogs of geologically stable surfaces is underway, but these types of designs have not been tested or deployed.

Range of Applicability: All cover designs.

Needed R&D: (1) Development of written guidance and technical assistance from geologists and soil scientists for characterizing geomorphic and pedogenic processes at a landfill site. (2) Field tests of alternative designs that incorporate drainage networks into a cover.

Sources:

Smith, G.M., W.J. Waugh, and M.K. Kastens, 1997. Analog of the long-term performance of vegetated rocky slopes for landfill covers, pp. 291-300. In: Tailings and Mine Waste '97, A.A. Balkema, Rotterdam.

Rhode, D., S. Sharpe, E. McDonald, and T. Bullard, 2001. FY 2002 Work Plan for Natural and Archaeological Analog Studies at the CRECLA Waste Disposal Cell, Monticello, Utah: Effects of Climate Variability and Soil-Geomorphic Processes On Long-term Cover Performance. Desert Research Institute, Reno, NV.

Waugh, W.J., K.L. Petersen, S.O. Link, B.N. Bjornstad, and G.W. Gee, 1994. Natural Analogs of the Long-term Performance of Engineered Covers, pp. 379-409. In G.W. Gee and N.R. Wing (eds.), In-Situ Remediation: Scientific Basis for Current and Future Technologies. Battelle Press, Columbus, OH.

Technique/technology # 5

Title: Ecologically Sustainable Designs

Ecological development on covers is inevitable. Current engineering approaches fail to consider either the deleterious or beneficial effects ecological processes may have on the long-term performance of covers. Seeding of monocultures or low-diversity vegetation on engineered covers is common. Instead, revegetation should attempt to emulate the structure, function, diversity, and resiliency of reference ecosystems.

Current maturity level: The principles and practices of restoration ecology and mine land reclamation are very well developed but have not been fully integrated into cover design process.

Range of Applicability: All cover designs

Needed R&D: Development of written guidance and technical assistance from restoration ecologists and reclamation specialists will accelerate integration of these techniques into the engineering of long-term covers.

Sources:

- Allen, E.B. (ed.). 1988. The Reconstruction of Disturbed Arid Lands: An Ecological Approach. AAAS Selected Symposium 109, American Association for the Advancement of Science, Washington, D.C.
- Anderson, J.E., and R.S. Inouye, 2001. Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. *Ecological Monographs* 71:531-556.
- Barnhisel, R.I., R.G. Farnmody, and W.L. Daniels. 2000. Reclamation of Drastically Disturbed Lands. Agronomy No. 41, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin.
- Covington, W.W., and L.F. DeBanco (eds.). 1994. Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management. USDA Forest Service General Technical Report RM-247, Rocky Mountain Forest and Range Experiment Station, U.S. Department of Agriculture, Fort Collins, CO.
- Link, S.O. 2001. FY 2002 Work Plan for a Field Demonstration of Baseline Ecological Studies at the Monticello, Utah Superfund Site: Revegetation Design, Performance Monitoring, and Effects of Ecological Change On Long-term Cover Performance. Washington State University-TriCities, Richland WA.

Technique/technology # 6

Title: Phytoremediation Caps.

A phytoremediation cap is a type of “smart storage”, a system that integrates containment and treatment. Plants growing in a soil cover are used to manipulate hydraulic gradient and prevent recharge as with ET caps (containment), but also to stabilize or detoxify the contaminants (treatment). The idea is that, waste stabilization or treatment will shorten the necessary period of isolation or containment.

Current maturity level: Phytoremediation is a developing technology but with several deployments. Phytoremediation caps are primarily conceptual; field tests and demonstrations are needed.

Range of Applicability: Where both phytoremediation and hydraulic manipulation are needed.

Needed R&D: (1) Survey applicability of phytoremediation caps within the DOE complex. (2) Field tests of the installation and performance of phytoremediation caps are needed. (3) Develop methods to monitor treatment to determine when containment is no longer needed.

Sources:

- Looney, B. (ed.), 2002. Technical Targets: A Tool to Support Strategic Planning in the Subsurface Contaminant Focus Area. WSRC-RP-2002-00077, Westinghouse Savannah River Company, Aiken, SC.
- U.S. Department of Energy, 2000. Proceedings from the Workshop on Phytoremediation of Inorganic Contaminants, November 3 – December 2, 1999, Argonne National Laboratory, Chicago, Illinois. INEEL/EXT-2000-00207, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

U.S. Environmental Protection Agency, 2000. Introduction to Phytoremediation. EPA/600/R-99/107, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Waugh, W.J., and E.P. Glenn, 2002. Phytoremediation of Nitrogen Contamination in Subpile Soils and in the Alluvial Aquifer at the Monument Valley, Arizona, Uranium Mill Tailings Site. GJO-2002-312-TAR, UMTRA Ground Water Research Project, U.S. Department of Energy Grand Junction Office, Grand Junction, CO.

Technology Pathway Summary (Form B)

Capability to be improved: 2.2a Design, build, and operate alternative containment systems (cover)

Associated Target(s): 2.2a Deploy *cover systems* that mimic natural processes and accommodate environmental change.

This technology pathway is closely tied to *Capability and Target 4.1* which includes an integrated technology pathway for both. In an effort to directly support the EM Thrust Areas, the following technology pathway summary outlines specific steps for incorporating methods *to mimic natural processes and accommodate environmental change* in the process of designing ET caps for the Rocky Flats Environmental Technology Site.

1. Review Existing RFETS Cover Design and Performance Criteria

- a. Review RFETS data on contaminant sources, mobility, and release and exposure scenarios. Determine whether cover performance criteria have been established (e.g. maximum allowable drainage flux).
- b. Review the proposed evapotranspiration (ET) cover designs for RFETS. Review the performance assessment models and engineering calculations RFETS plans to implement in the cover design process for soil water balance, evapotranspiration, erosion, revegetation, etc.
- c. Review baseline (current) environmental setting information such as site geomorphology (e.g. surface and slope stability) physical and hydraulic properties of borrow soils, existing vegetation, and burrowing animal habitat.
- d. Determine key input parameters for engineering, performance assessment, and performance monitoring of the RFETS ET cover (e.g. soil water storage capacity, saturated hydraulic conductivity, monthly precipitation, etc).
- e. Develop criteria for selecting analog sites for long-term changes in climate, geomorphology, soils, and ecology.

Prerequisites—An agreement with RFETS to collaborate with the Principal Investigator of ASTD Proposal Number SC-17, “Rocky Flats Environmental Technology Site Proposal for Implementation of Evapotranspiration Covers.”

Expected Products /Results—Compilation of baseline ecological information for RFETS ET covers, cover design and performance standards, performance modeling and monitoring requirements, and analog site selection criteria.

Duration—3 months.

Cost—\$25,000.

2. Climate Change Investigation

- a. Characterize modern climate for RFETS including historical meteorological records and response to historical changes in atmospheric circulation (e.g., El Nino and La Nina years). Obtain maps of modern climate for the region.
- b. Review projected global/regional climate change scenarios and ranges of potential future climate states (temperature, precipitation, seasonality, extremes).

- c. Search paleoclimate literature for ranges of past climate states that are analogous ranges of global/regional change scenarios.
- d. Define key future climate states for *direct* input to performance modeling and monitoring
- e. Define key future climate states for *indirect* (secondary) impacts on cover performance for input to analog site selection (e.g. what climate end states would most impact other performance processes such as erosion, soil development, plant community development, burrowing animal habitat, etc.).
- f. Develop GIS layer indicating, regionally, where potential analog sites may exist representing key future climate states.

Prerequisites—Task 1.

Expected Products /Results—Reasonable range of possible future climate states and extremes for Rocky Flats based on existing paleoclimate literature and global climate change models for input to (1) cover performance models and (2) analog site selection (Task 3).

Duration—6 months.

Cost—\$50,000.

3. Analog Site Reconnaissance

- a. Acquire local/regional geologic maps, soil surveys, topographic maps, vegetation maps and floras, air photos, satellite imagery, etc. for the RFETS area and for analogs of future climate states.
- b. Develop GIS layers for existing vegetation, geomorphology, and soils for the RFETS area and for areas analogous to future climate states.
- c. Search literature for land use history and archaeological sites/resources that may provide chronological control for understanding rates of geomorphology/soil develop and ecological succession for the 1000-year design life of RFETS covers. Create land-use/archaeology GIS layers.
- d. Use existing resources, the analog-site GIS, and selection criteria to locate and rank potential analog sites.

Prerequisites—Tasks 1 and 2.

Expected Products /Results—GIS maps of locations to search for sites that are reasonable analogs of possible future ecological conditions on the RFETS ET covers.

Duration—3 months.

Cost—\$25,000.

4. Analog Site Characterization

- a. Characterize hillslope settings analogous to the geometry and materials proposed for the RFETS ET covers. Develop a conceptual model and then characterize geomorphological processes that would likely have the greatest impact on the engineered cover. Characterize geomorphological settings exhibiting favorable attributes of long-term stability (e.g. rock/soil armored slope with a favorable soil water balance) that could be incorporated into the cover design.
- b. Characterize analog-site soil profiles (natural and archaeological soil profiles if they exist) to identify pedogenic processes (e.g. bioturbation and soil structural development) that could impact the performance of the RFETS cover over its 1000-year design life. Measure key performance

assessment parameters in analog soil profiles such as hydraulic conductivity and water storage capacity.

c. Characterize ecological analogs.

- Choose and characterize reference plant communities that represent the potential vegetation for the cover and that can be used as a revegetation target.
- Identify and rank types of secondary perturbations for the site such as fire, grazing, invasion of exotic species, cultivation, etc. Characterize vegetation chronosequences for key disturbances.
- Locate and characterize analogs of ecological responses to potential future climate states. Characterize key vegetation parameters impacting performance such as canopy cover, leaf area index, and root length density. Also characterize habitat for burrowing animals and impacts of burrows and tunnels on cover performance (e.g., effects on macropore flow and soil displacement).

Prerequisites—Task 3.

Expected Products /Results—

- Baseline geomorphological and ecological data for input to the ET cover engineering and revegetation designs at RFETS.
- Soil (physical and hydraulic properties) and vegetation (plant community structure and ecophysiology) data from analog sites for input to soil water balance and erosion models as part of a long-term performance evaluation for the RFETS ET cover.

Duration—12 months.

Cost—\$125,000.

5. *Incorporate Analog Site Data and Existing Alternative Cover Study Results into the RFETS ET Cover Design Process (see ASTD Proposal Number SC-17, “Rocky Flats Environmental Technology Site Proposal for Implementation of Evapotranspiration Covers.”)*

- a. Use results of Tasks 1 – 4 to provide ET cover design recommendations including the feasibility of incorporating aspects of the technologies discussed on Form A: biointrusion barriers, rock/soil armoring, water balance designs, geomorphological geometry, and ecologically sustainable designs
- b. Evaluate possible future changes in the condition of RFETS ET covers based on characterization of natural analogs (Tasks 1-4).
- c. Create input data files for long-term performance modeling of RFETS ET covers.

Prerequisites—Tasks 1-4.

Expected Products /Results—Design and performance assessment data sets, recommendations, and technical assistance for RFETS ET covers.

Duration—3 months.

Cost—\$50,000.

2. Limit Intrusion, Transport, Release, and Exposure

Technical Approaches (Form A)

Capability to be improved: 2.2b Design, build and operate alternate containment systems in the subsurface.

Associated Target(s): 2.2b Deploy subsurface containment systems that mimic natural processes and accommodate environmental change.

Technique/technology # 1

Title: Geologic material based leachate collection and leak detection systems.

Current maturity level: This is a mature area of application. While the use of geosynthetic media has been common in recent years, geologic materials i.e. gravel and sand have been utilized in projects with long design lives like the Fernald LTDF. There remains room for some additional study to fine-tune and refine the capability to reduce long-term failures by clogging.

Range of Applicability: Municipal solid waste (MSW), UMTRA, Low-level waste, mixed waste, hazardous waste.

Needed R&D: Forensic study of the performance of systems that have been in use is needed. Much of this data might come from existing MSW and hazardous waste sites outside of the complex.

Sources:

Technique/technology # 2

Title: Passive-reactive Barriers and enhanced biological treatment barriers

Current maturity level: Medium. Some applications in the field are in place and functioning.

Range of Applicability: Relatively wide, mainly utilized with organic contaminants to date, could also be useful with inorganic materials, particularly metals and mixed wastes.

Needed R&D: Bench and pilot testing for specific contaminants and waste mixtures. Further research is needed for inorganic contaminants.

Sources:

Technique/technology # 3

Title: Slurry walls, grout curtains, bottom seals and enhanced barrier clogging

Current maturity level: Relatively mature except for enhanced barrier clogging which is in an early stage of development. In-situ placement of horizontal barriers is not yet mature, but could draw on use in other industries such as utility installation.

Range of Applicability: Wide range of wastes and settings.

Needed R&D: Study is needed of sustainability over time, and on application of systems with primary reliance on native/natural geologic materials and microorganisms. Study is also needed regarding the applicability of in-situ horizontal barrier construction. This should utilize information on direction drilling technologies.

Sources:

Technique/technology # 4

Title: Deep-rooted phyto-hydraulic control and pumping for hydraulic control

Current maturity level: Somewhat mature.

Range of Applicability: Wide range of use particularly applicable to vadose zone.

Needed R&D: Testing and application to optimize species selection and related maintenance issues to sustain species: i.e. fires for prairies, enhanced symbiosis to promote natural sustainability

Sources:

Technique/technology # 5

Title: Frozen soil barriers

Current maturity level: Mature technology for other applications such as tunnel and shaft support. Has not been applied to contaminant migration problems, although it has been tested as part of the SITE Demonstration Program at Oak Ridge National Laboratory. .

Range of Applicability: Wide variety of contaminants and wastes. May be limited in long term applications due to energy requirements

Needed R&D: Further field tests are necessary to more completely evaluate this technology.

Sources:

<http://www.clu-in.org/products/site/ongoing/demoong/arctic.htm> - EPA technology profile of the "Cryogenic Barrier", written before testing began.

<http://www.wpi.org/Initiatives/init/oct97/> - "Will frozen barrier stop plume in its tracks?" (1997)

<http://www.ct.ornl.gov/stcg/nls97.htm> - "Cryogenic Barrier is Being Installed and Tested on a Superfund Site at ORNL" (summer 1997)

Technique/technology # 6

Title: Capillary barriers.

Current maturity level: Med high range of maturity. Used in disposal facility covers, and in underdrain systems. Principle is widely used in building construction for moisture barriers below concrete slabs on grade. Use in horizontal or vertical barriers in contaminant control is less mature.

Range of Applicability: Relatively wide range of wastes, and contaminants, particularly applicable in the vadose zone.

Needed R&D: Technical basis can readily be adapted from other applications of this technique. Physical principals are basic and straightforward. Demonstration projects are needed. Development of technology guidance documents are desirable as well.

Sources:

Technology Pathway Summary (Form B)

Capability to be improved: 2.2b Design, build and operate alternate containment systems in the subsurface.

Associated Target(s): 2.2b Deploy subsurface containment systems that mimic natural processes and accommodate environmental change.

1. Review Existing Knowledge Base. This will include a review of the existing literature, discussions with project Principal Investigators, and discussion with site managers that have LTS needs. Information developed from current site remediation activities such as Rocky flats or Fernald should be coordinated, recognizing the limitations of each site on applicability to other sites.
 - **Prerequisites**—All that is needed to initiate this task is a decision to invest in the research area.
 - **Expected Products / Results**—The product of the review will be an understanding of the status of the need for research in this area, current maturity, and gaps in the science needed to develop this technology.
 - **Duration**—The duration of this task should be no longer than 6 months.
 - **Cost**—Cost should not exceed \$200,000. Even this cost is high for review of knowledge. However, there are a wide variety of potential technologies, some of which are very new others more established, with a corresponding variation in availability of information.
2. (a) Conduct Proof of Concept. Lab scale (or garden scale) testing of containment technologies theories (on simulants most likely), analysis of results, efficiency improvements, reformation to workable systems.
 - **Prerequisites**—Completion of the Task 1 studies to allow definition of the knowledge base and the ideas to test for verification of concept.
 - **Expected Products / Results**—In coordination with Task 2b the product should be an understanding of performance at small scale and under idealized conditions.
 - **Duration**—Owing to the need to deal with growing seasons, this task is estimated to last at least two years. However, much can be learned in the first year, which could allow for initiation of subsequent tasks during year two if determined to be desirable.
 - **Cost**—Cost should be in the area of \$1,000,000. Some techniques will require little or any bench scale testing as they are already fairly mature techniques thus reducing overall costs.
2. (b) Develop Predictive Models. Merge theory with experiments in Task 2a to guide Task 2a and to be guided by results of Task 2a. Key synergism of the two tasks.
 - **Prerequisites**—To allow definition of the knowledge base and development of the concept of system configuration and thus the modeling capability necessary.
 - **Expected Products / Results**—In coordination with Task 2a the product should be an understanding of performance at small scale and under idealized conditions. However, the

modeling component should also allow for evaluation of the effect of changes in conditions governing performance of the systems.

- **Duration**—This task runs concurrently with Task 2a and the duration will essentially be the same. Model development can be largely be completed in year one, except for those technologies utilizing phyto based techniques, in that case the models should be refined in year two.
- **Cost**—Cost should be approximately \$500,000, as models should not be overly complex and can draw on existing models as a foundation with fine tuning based upon small scale studies conducted in Task 2a.

3. **Pilot Testing.** Scale up from bench (garden) studies, add more realism by using real waste, but still keep some idealism for the capability to work.

- **Prerequisites**—Completion of the Task 2a and 2b studies with good results, funding buy-in to the viability of the concept, a site to use for field-testing, and regulatory approval.
- **Expected Products / Results**—The end result will be a scaled up proof of concept that includes more real-world issues and uncertainties, heterogeneities, etc.
- **Duration**—Again the duration should allow for several growing seasons. The minimum duration should be 2 years. Longer duration of maintenance and data collection are strongly recommended.
- **Cost**—Cost will be highly dependent on the size of a field test location, which directly impacts construction costs and also has a direct impact on monitoring, maintenance and operations costs. An amount of \$2,000,000 seems to be reasonable with more funds possibly being needed for longer term testing and monitoring.

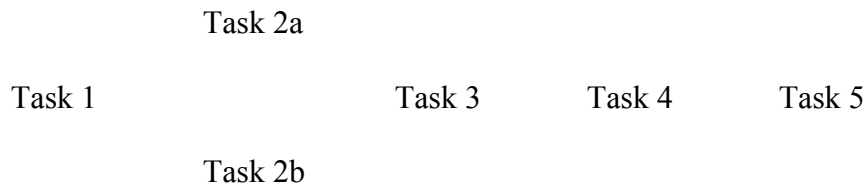
4. **Scaling and Deployment.** Engineering analyses, cost analysis, building of systems, licensing to contractors, secure test site, attain regulatory approval, and test on real contaminants.

- **Prerequisites**—Successful pilot level testing in Task 3, regulatory buy-in, deployment site, and funding buy-in.
- **Expected Products / Results**—The expected product is a successful demonstration project with knowledge gained regarding limitations of the system and needs to make changes to fine-tune future deployments.
- **Duration**—Again the duration must allow for several growing seasons. The minimum duration should be 2 or 3 years. Longer duration of maintenance and data collection are strongly recommended particularly for this field trial. It seems likely that longer term monitoring will be required to obtain regulatory approval in any event.
- **Cost**—Cost will be highly dependent on the size of a field test location, which directly impacts construction costs and also has a direct impact on monitoring, maintenance and operations costs. An amount of \$3,000,000 to \$4,000,000 seems to be reasonable.

5. **Post Deployment Validation.** Monitor system, understand maintenance and repair issues, operational costs and issues, complete performance comparison with alternative technologies, and publish results to widely distribute knowledge gained, including the preparation of guidance documents.

- **Prerequisites**—Successful site deployment under Task 4.
- **Expected Products / Results**—Adoption of technique as one of a group of potential long term remediation and stewardship strategies, Regulatory acceptance as a viable technology (system) that in no longer considered experimental.
- **Duration**—One to two years to continue monitoring of deployment site performance and allow for technology transfer.
- **Cost**—\$500,000 to \$750,000. Longer term monitoring is mainly in the area of confirmation of models and findings, and thus is utilized to ‘fine-tune’ earlier conclusions. As no new construction is needed costs are reduced to data collection and analysis and maintenance.

Basic task relationship layout is the following. Note that Task 2a and 2b should have interdependencies.



(Please excuse my limited knowledge of producing graphics in a word file. I will work on getting something more final sent out soon.)

4. Predict, Monitor, and Evaluate System Performance

Technical Approaches (Form A)

Capability to be improved: 4.1 Conceptualize and predict system performance and potential failure modes / levels of failure.

Associated Target(s): 4.1 Deploy a “toolbox” of techniques and technologies (e.g., models, natural analogs, performance indicators, failure criteria, and guidance) to improve planning, decision making, design, monitoring, maintenance, and interpretation of monitoring data.

Understanding the behavior of contaminated materials within the environmental settings unique to each stewardship site – which will continue to change over time – is crucial to identifying and implementing appropriate containment and control options and promoting the sustainability of these protective systems. This capability involves conceptualizing the integrated natural and engineered systems, enhancing predictive tools for evaluating CC&C system performance and understanding failure initiators, using natural analogs to predict environmental conditions and CC&C system responses over the long term, and incorporating this information into the ongoing design and refinement of these systems. The key emphasis is harmony with the natural environment, so CC&C systems work with and rely on natural processes rather than countering them.

An overview of the techniques/technologies within this capability is provided in Figure 1. This capability and target are closely linked with and support each of the others in the CC&C Work Group (1.4a, 1.4b, 2.2a, 2.2b, and 5.1), and interrelationships also exist among the individual techniques/technologies listed in this subsection. In addition, information from these capabilities flows to and from those of the other work groups.

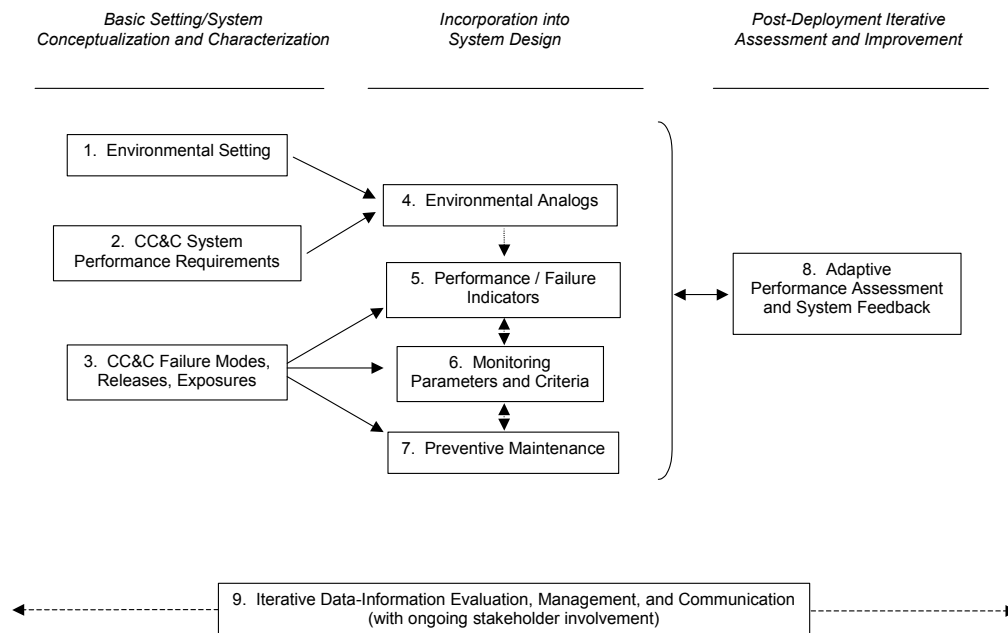


Figure 1. Overview for Capability 4.1a: Predict, Monitor, and Evaluate System Performance.

Technique/technology # 1 (Environmental Setting)

Title: Characterize Current Environmental Settings and Predicted End States.

Understanding current and projected environmental states at each stewardship site is needed to identify reasonable ranges for long-term changes that could lead to failure of CC&C systems over time. These conditions cover five major categories: (1) climate change; (2) ecological succession; (3) pedogenesis (including soil structure and horizon development, bioturbation, dessication, and freeze-thaw cracking); (4) landform processes (such as uplift resulting in topographic changes); and (5) land use, with primary emphasis on the next few generations. Also essential to this characterization is an understanding of how site contaminants behave in these settings. This characterization effort covers (1) transformation and attenuation (to more or less toxic forms, including through radioactive decay, biodegradation, hydrolysis, and photolysis); (2) mobility (including adsorption, fixation, and complexation); and (3) bioavailability, also considering uptake, transfer, and other partitioning factors.

Current maturity level: Basic environmental characterization and prediction methods are well developed and demonstrated. However, they have not yet been integrated across categories or sufficiently verified to provide the information needed for long-term CC&C systems. Similarly “immature” is the level of data available to address site-specific stewardship needs, including information on the behavior of contaminants and of systems that have been installed.

Range of Applicability: All stewardship sites.

Needed R&D:

A. For natural environmental settings:

1. Compile a *catalog* of current environmental states and ranges of predictions and associated uncertainties for future states across the five categories. For example, for climate change assemble information and projections for temperature, precipitation, seasonality, and extremes for each site region.
2. Develop *methods and tools* for combining these predictions to provide an integrated view, or preview, of future states for these site regions.
3. Develop *methods and tools* for history matching or hindcasting of integrated environmental conditions (e.g., using Monte Carlo and Bayesian approaches), and conduct this activity for each site region using data and proxies for past conditions to reduce the ranges of uncertainty in the compiled values.
4. Develop *guidance* for identifying and mapping analog sites and conditions and defining reasonable ranges for key characteristics within each of the five categories, and prepare an *atlas* of these maps and ranges for each site region.

B. For environmental contamination and control systems:

1. Compile existing site-specific data and identify key information still needed to reasonably address long-term stewardship questions, including through risk estimation and sensitivity analyses using current models and approaches. Prepare a *protocol* for collecting site-specific data to address these needs, incorporating both stakeholder involvement and the data quality objective (DQO) process.
2. Collect new site data to fill the key gaps, to include consideration of the following (highlighted from Field presentations to the work groups in Orlando).
 - a. Source characteristics

- waste site boundaries and contents (including transuranic waste, fuel pools, asbestos, debris); fingerprinting to distinguish from background, other sources
- subsurface facilities (including location and nature of piping)
- surface facilities: physical hazards (structural stability) and biological and chemical hazards (ambient concentrations in indoor air, and moisture and temperature conditions conducive to biohazards, such as mold and mildew, hanta virus, and bubonic plague, and vectors such as mice, rats, and cockroaches)
- b. System characteristics, including barriers and treatment
 - intrusion deterrents and observations of changes in installed caps/covers
 - in-situ stabilization through better injection and dispersion of better agents
 - treatment to isolate metals and radionuclides, treatment of DNAPLs
 - preservation of cover integrity when monitors are emplaced and replaced; better predictions to reduce uncertainty for covers and barriers
 - “minimum-safe” post-closure requirements
- c. Release, transport, and fate characteristics, including hydrologic and other isolation
 - leachate flow and quality; flow in fractured media
 - decommissioning of groundwater wells and potential for preferential flow
 - adsorption and other attenuation characteristics, including capacity of soil
 - bioavailability of environmental contamination, effective biological half life

These characterization activities would be coordinated and conducted in parallel, such that the *methods, tools, and guidance* efforts described for the natural environmental setting (A.2-4 above) would also be conducted for conceptualization and characterization of “environmental contamination” and “control system” settings.

Links:

With Other CC&C Capabilities:

- 1.4b, Engineer Biogeochemical Environment (ground water environment): Provide up-front conceptualization and characterization of environmental setting and contaminant conditions and how they may change over time, with an emphasis on the subsurface, to support the feasibility and effectiveness evaluations of engineering options (such as reagent injection) for limiting contaminant toxicity and mobility.

With Other Work Groups:

- *Decision Making and Institutional Performance (DMIP) and Safety Systems and Institutional Controls (SSIC):* Solicit and share information on the current state and reasonable range of projected land uses, with primary emphasis on near-term generations, for consistency and to limit the potential for pieces to “fall through cracks” (for the human element of the environment). Solicit input to the identification of key data gaps and data collection protocols, and provide newly collected data as scoping input.
- *Monitoring and Sensors (M&S):* Solicit information on larger-scale physical, biological, and chemical environmental monitoring and sensing to support hindcasting and characterization. Monitoring data and projections for land use (e.g., from remote sensing and predicted population patterns) are also included here if not already provided by DMIP and SSIC. Solicit input to the identification of key data gaps and data collection protocols, and provide newly collected data as scoping input.

Sources:

Technique/technology # 2 (System Performance Requirements)

Title: Identify CC&C System Performance Requirements

Current maturity level: Basic methods for identifying generic performance requirements for engineered containment and control systems are well developed. However, they do not yet fully account for environmental settings and other local factors, nor are they being deployed for sustained effectiveness and efficiency over successive generations.

Range of Applicability: All stewardship sites.

Needed R&D:

1. Compile performance requirements for existing systems, extending beyond DOE to include commercial and municipal systems. Also compile information on the systems' abilities to achieve these requirements and active measures that have been taken to sustain performance, considering factors such as component reliability, time-to-correct or replace, ease-of-correction or replacement, and cost. Include key elements that affect performance, considering both those that sustain it and those that weaken it. Provide this information in a *"performance status" resource report*.
2. For sites that have not yet implemented CC&C systems: conceptualize and summarize contamination-setting-system configurations for both baseline and alternate systems; improve *methods and tools* for predicting system control capabilities (e.g., for controlling infiltration, leaching, drainage flux; gas release; slope instability, subsidence; erosion, soil loss; and biotic and human intrusion in arid, semi-arid, and humid settings); improve *methods and tools* for identifying system features critical to performance and reasonable ranges of performance. Provide this modeling and other predictive information in a *"conceptual performance requirements" resource report*.
3. Develop a *method* and *protocol* for soliciting and incorporating user, provider, and stakeholder needs and issues into system requirements to identify reasonable performance envelopes.
4. Develop a *guide* for defining and refining performance requirements for specific CC&C systems that considers system response to environmental change.

Links:

With Other CC&C Capabilities: Provide improved front-end conceptualization and understanding of the surface and subsurface environment, the contamination, and the engineered system, including how the risk-driving components of each can change over time and what responses are needed. Support site-specific integration of these elements to result in effective and efficient CC&C systems. Links with all five CC&C capabilities, with the first three being primary:

- 2.2a Design, build, and operate alternate containment systems (cover barriers)
- 2.2b Design, build, and operate alternate containment systems (subsurface barriers)
- 5.1 Identify and implement improved responses to change (via routine and

preventive maintenance that nurtures system performance) and failure (via corrective repair, retrofit, and replacement)

- 1.4a Engineer Biogeochemical Environment (ground water environment)
- 1.4b Engineer Biogeochemical Environment (source)

With Other Work Groups:

- *DMIP*: Provide conceptualization of integrated system (source, setting, engineering measures) to support related stakeholder discussions. Solicit results of stakeholder involvement and incorporate those needs and issues into CC&C performance requirements guide and protocol.
- *SSIC*: Provide conceptualization of integrated system as scoping input to the evaluation of safety systems and access controls, including information for the target contaminant list based on site-specific risk factors (considering source, setting, and expected capabilities of engineered controls). Solicit results of that evaluation to incorporate into the performance requirements guide and protocol. As above, solicit input to and results of stakeholder involvement.
- *M&S*: Solicit results from performance monitoring of existing systems. Provide conceptualized configurations, key elements, designed control capabilities, and reasonable performance envelopes as scoping input to the development of new monitors and sensors. Solicit capabilities that can support enhanced system performance monitoring to incorporate in the guide and protocol.

Sources:

Technique/technology # 3 (Failure Modes, Releases, Exposures)

Title: Identify System Failure Modes, Release Processes, and Exposure Pathways

Current maturity level: Basic methods for identifying generic failure modes and release processes are well developed. So are general, idealized transport and fate models and a standard exposure assessment methodology. However, these are not yet integrated across the whole system (waste source, CC&C configuration, and environmental setting), nor have they been validated or verified for site-specific conditions. Also, current models still represent fairly simple cases and are not yet well enough developed to accurately represent real, heterogeneous environments (such as flow in fractured media / other preferential flows, site-specific attenuation characteristics, or susceptibility to and recovery from exposure effects.)

Range of Applicability: All stewardship sites.

Needed R&D:

1. Compile a *resource handbook* of information and models for the following.
 - a. Failure events and conditions, with probabilities, consequences, and uncertainties
 - natural events by region, such as earthquakes, fires, floods, and damaging winds
 - engineered system (whole and components) failure modes and initiating conditions
 - b. Release process and transport and fate models, to focus on risk drivers
 - c. Exposure pathways and associated risks

2. Prepare a *guide* for enhancing and linking models of coupled processes, incorporating probabilistic and Bayesian approaches. Include in the guide *checklists* for maintaining overall fidelity across models, as well as illustrative *examples*.
 - a. Failure event probability / consequence models
 - b. System performance / risk models
 - c. Ecosystem/water balance models
 - d. Release, contaminant transport and fate, hydrobiogeochemical models
 - e. Exposure / effect models (e.g., to incorporate susceptibility knowledge emerging from genomics, proteomics, cumulative risk studies)
3. Run linked models and conduct sensitivity analyses, and use results to refine *methods and tools* for identifying further site-specific data needed to reduce the range of key uncertainties, and thus conservatism in system designs. Prepare a *protocol* for collecting these additional data, incorporating stakeholder involvement and the DQO process.
4. Collect the needed site data and incorporate them into improved *coupled models*, making them relevant and more capable of reasonable predictions. This involves further conceptualization and numerical modeling, model integration, and verification/validation. Provide these models and results in tiered *guides* to represent the overall system and its components, capturing failure modes, release processes, and potential exposure issues. (For example, an umbrella report or primer would cover broadly common elements and could be complemented by regional or site-specific guides that cover additional location-specific features.)
5. Develop *methods and guidance* for scoring the significance of system conditions that reflect different stages (from precursor to full) of different modes of failure, and for linking these to monitoring and countermeasure protocols. These should incorporate stakeholder involvement and be geared to site-specific application considering expected and alternate source-setting-system configurations.

Links:

With Other CC&C Capabilities:

- 1.4, 2.2, 5.1: Provide better system conceptualization and coupled models (improved by site-specific data) to guide analysis and selection of system design, operation, and maintenance.

With Other Work Groups:

- *M&S*: Solicit input on system failures and conditions, the scoring method, and the approach for linking to monitoring protocols. Provide model results and key site/system data as scoping input for monitor and sensor development.
- *SSIC*: Solicit input on and results of land use control and projected receptor analyses (access/ exposure restrictions), and on stakeholder involvement processes and the results of those involvements. Solicit input on failure modes for institutional controls, including probabilities, consequences, and uncertainties. Solicit input on the scoring system, link to countermeasures (and monitoring if not addressed by M&S). Provide model results and key site/system data as scoping input for safety systems and institutional controls.
- *DMIP*: Solicit input on failure modes for institutional systems (as described above for institutional controls) and on the scoring system and link to countermeasures. Solicit input on stakeholder involvement processes and the results of those involvements.

Provide model results and key site/system data as scoping input for decision making and institutional performance.

Sources:

Technique/technology # 4 (Environmental Analogs)

Title: Identify and Integrate Analogs of Long-Term Environmental Change into System Design

If location-appropriate analogs of natural processes were fully incorporated into CC&C system design, it would greatly strengthen system resilience to environmental changes, which we know will occur. Not only will these alternate systems be much more effective, they will be much cheaper than current systems which require extensive active management to offset the impacts of natural processes.

Current maturity level: Methods for identifying natural analogs are reasonably well developed for a range of system features. However, methods for integrating these analogs into CC&C systems for sustained effectiveness over the long term are not yet well developed and are not yet widely deployed.

Range of Applicability: All stewardship sites.

Needed R&D:

1. Develop *methods and tools* for identifying environmental analogs to support the long-term viability of CC&C systems, and compile an *analog catalog* – a set of environmental analogs by resource and location/region with associated ranges and uncertainties (e.g., for geologic/ slope stability, vegetation and sustained water balance, and biointrusion resistance).
2. Develop *methods and protocols* for designing and implementing accelerated (“compressed-time”) tests that simulate future environmental conditions, to evaluate resilience of baseline and alternate CC&C systems.
3. Synthesize results of bench-scale and pilot tests of simulated system performance in a *case study summary* to facilitate identification of natural design features that accommodate long-term change for specific systems. Using these results, develop *methods and tools* for identifying key system elements for various source-system-setting configurations and the optimum analogs for those elements, with expected ranges and uncertainties.
4. Develop *methods* for integrating analogs of long-term environmental change into CC&C systems. Prepare *protocols* for design teams to implement on a site-specific basis that include opportunities for stakeholder input (e.g., an umbrella primer and tiered guides).

Links:

With Other CC&C Capabilities:

- 2.2 (primary)
- 5.1, 1.4 (secondary)

With Other Work Groups:

- *M&S*: Solicit past monitoring and sensing data for long-term change and expectations of data generated by ongoing or planned studies. Solicit input to and provide the design guide, and also case study information, as scoping input for monitor and sensor development.
- *SSIC*: Solicit input regarding changes in land use controls (access/exposure restrictions). Solicit input on protocols for obtaining and incorporating stakeholder input, and solicit results of stakeholder involvement activities. Provide case study and other information as scoping input for safety systems and institutional controls.
- *DMIP*: Solicit input on obtaining and incorporating stakeholder input and solicit results as above. Provide case study and other information as scoping input to decision making and institutional performance.

Sources:

Technique/technology # 5 (Performance / Failure Indicator)

Title: Identify and Integrate Performance and Failure Indicators into CC&C Systems.

Indicators are needed to assure that individual components (e.g., barrier, collection, and treatment components) and whole systems are operating within expected performance envelopes. Indicators are also needed to identify when the system is failing, including early warnings or precursors. Chemical, geophysical, and biological indicators must be integrated during the design and construction phases of new systems or the maintenance and upgrade phases of current systems to achieve effective, efficient CC&C for the long term.

Current maturity level: The methods and tools for identifying short-term performance and failure indicators are reasonably well developed (e.g., for solid and municipal waste landfills and mill tailings cells). However, they are not well developed for complex systems and have not yet been deployed to reliably indicate performance and failure over the long term.

Range of Applicability: All stewardship sites.

Needed R&D:

1. Compile definitions and indicators of performance and failure used for existing systems, as well as those planned for systems being designed and implemented. Provide these in a general “*indicators*” *reference report*.
2. Conceptualize and develop integrated *methods and tools* for understanding system behavior over a reasonable range of environmental setting and system conditions in order to define key failure points, using updated and enhanced models with probabilistic and Bayesian approaches. Prepare a *reference handbook* of these modeling approaches to cover all major source-system-setting configurations; also in this handbook identify important performance and failure indicators for baseline and alternate CC&C systems as indicated by model simulations.
3. Collect site and system data to improve these *models*, extending them from generalized laboratory conditions to field conditions, identifying key vulnerabilities and reducing uncertainty ranges (and related design conservatism). Develop *methods and tools* to evaluate indicators and surrogates of performance and failure in the context of natural environmental changes, to include comparative analyses for reference sites.

4. Develop improved *methods, tools, and protocols* for identifying, prioritizing and selecting core performance and failure indicators and surrogates on a site-specific basis, to include input from users, providers, and stakeholders.
5. Develop *methods, tools, and protocols* for incorporating selected indicators or surrogates of performance and failure into CC&C systems – as part of the design-construction phase for those in development, and as part of the upgrade phase for those already in place.

Links:

With Other CC&C Capabilities:

- 2.2, 5.1 (primary)
- 1.4 (secondary)

With Other Work Groups:

- *M&S*: Solicit input on performance and failure indicators for CC&C systems per current monitoring information, and provide the reference report and handbook as scoping input for monitor and sensor development. Solicit input on methods for evaluating, prioritizing, and selecting core indicators and for incorporating them into systems, and provide these methods as scoping input to M&S development.
- *SSIC*: Solicit input on the performance and failure of safety systems and institutional controls, and on obtaining and incorporating stakeholder input to methods and protocols. Provide the reference report and handbook, as well as methods and protocols, as scoping input for SSIC.
- *DMIP*: Solicit input on the performance and failure of institutional systems and stewardship decisions, and on obtaining and incorporating stakeholder input to methods and protocols. Provide the reference report and handbook, as well as methods and protocols, as scoping input for DMIP.

Sources:

Technique/technology # 6 (Monitoring Parameters and Criteria)

Title: Identify Monitoring Parameters and Criteria, and Integrate into CC&C Systems

Current maturity level: Methods for identifying monitoring parameters for basic CC&C systems are reasonably well developed, but they have not yet been tailored for nor widely implemented in complex systems designed for long-term protection. Similarly, methods for defining general criteria for these parameters are fairly well developed, but site-specific criteria using the DQO process have not been effectively deployed for complex systems.

Range of Applicability: All stewardship sites.

Needed R&D:

1. From existing systems, compile key parameters, ranges, uncertainties, and acceptable deviations. Conduct trend analyses that take into account environmental characteristics and other factors. Present this information in a *monitoring reference handbook*.

2. Develop improved *methods and tools* for identifying, prioritizing, optimizing, and selecting risk-driving parameters and surrogates to be monitored, such as cap moisture, infiltration, and outflow rate from reactive barriers. Address integrated area monitoring and remote sensing, incorporate stakeholder inputs, and consider the following:
 - a. Integrity and protectiveness of CC&C systems – surface and subsurface
 - b. Hazards – chemical, physical, & biological (e.g., invasive species, infectious agents)
 - c. Indicators of system stress, precursors of loss of effectiveness (e.g., vegetation changes)
3. Develop improved methods and tools for identifying, prioritizing, optimizing, and selecting quantitative criteria for these parameters, including reasonable ranges and acceptable deviations. Also develop improved methods and tools for threshold levels and triggers of different types or levels of response (e.g., blue = watch list, yellow = warning, red = action). Include provider, user, and other stakeholder inputs.
4. Develop improved methods and tools for identifying, prioritizing, optimizing, and selecting monitoring locations and frequencies, including for remote sensing (e.g., for contaminated materials ranging from buried transuranic waste to buildings and debris, and for environmental characteristics ranging from land use to vegetation and wildlife changes). Include provider, user, and other stakeholder inputs.
5. Develop streamlined methods and tools for acquiring, aggregating, integrating, evaluating, presenting, communicating, and archiving data, and for optimizing its reliability and utility (see T/T #9). Include provider, user, and stakeholder input.
6. Develop methods and protocols for integrating selected monitors and sensors into CC&C systems – during the design and construction phases for new systems and during the maintenance and upgrade phases for existing systems – and for refining or upgrading these monitors and sensors as dictated by system needs and the availability of more efficient and effective technologies. Include provider, user, and other stakeholder inputs.

Links:

With Other CC&C Capabilities:

- 2.2, 5.1 (primary)
- 1.4 (secondary)

With Other Work Groups:

- *M&S*: Solicit input from past monitoring activities for the reference handbook, parameters and surrogates, criteria, locations and frequencies, data and information management and communication, and refinement of M&Ss, and provide materials developed as input to M&S activities.
- *SSIC*: Solicit input from past monitoring activities, as described above but specific to safety systems and institutional controls. Include means for obtaining and incorporating stakeholder inputs.
- *DMIP*: Solicit input from past monitoring activities, as described above but specific to decision making and institutional performance. Include means for obtaining and incorporating stakeholder inputs.

Sources:

Technique/technology # 7 (Preventive Maintenance)

Title: Identify Preventive Maintenance Requirements and Integrate into CC&C Systems

Current maturity level: Methods for identifying preventive maintenance requirements are somewhat well developed. However, they have not yet been widely deployed to support efficient CC&C systems.

Range of Applicability: All stewardship sites.

Needed R&D:

1. Compile information on preventive maintenance requirements from existing operation and maintenance (O&M) plans and case histories, and prepare a *"status and lessons learned" resource report*.
2. Develop *methods and tools* for identifying, prioritizing, optimizing, and selecting measures for baseline and alternate CC&C systems under various source-setting-system configurations, to incorporate into system design. Incorporate user, provider, and other stakeholder input.
3. Develop *methods and tools* for system diagnosis and defining appropriate correction or repair measures for existing systems (both current ones and those to be implemented) over time, e.g., to (a) unclog drains, pipes, trenches; (b) remove scaling and de-foul surfaces; (c) re-seal transmission lines, implement self-healing barriers; (d) stabilize structures against physical deterioration; (e) seal/ activate automated self-treatment against biohazards; and (f) define mobile contingency treatment units. Incorporate user, provider, and other stakeholder input.

Links:

With Other CC&C Capabilities:

- 2.2, 5.1 (primary)
- 1.4 (secondary)

With Other Work Groups:

- *M&S:* Solicit input from past monitoring for the case histories and methods and tools, and provide materials developed as scoping input to M&S development, evaluation, and refinement.
- *SSIC:* Solicit input regarding safety systems and institutional controls for the case histories and methods and tools, and provide materials developed as scoping input to SSIC.
- *DMIP:* Solicit input regarding decisions and institutional performance for the case histories and methods and tools, and provide materials developed as scoping input to DMIP.

Sources:

Technique/Technology # 8 (Adaptive Performance Assessment and Feedback)

Title: Integrate Field Tests, Analogs, and Models for Performance Assessment and Feedback

The objective of CC&C systems at stewardship sites is to sustain protection over the long term. Thus, iterative performance assessments are needed to integrate ongoing field tests and analogs of system performance with predictive models, and a process is needed to ensure that resulting information is fed back to the system to guide appropriate modifications.

Current maturity level: Evaluation methods for field testing are well developed, as are general predictive models for performance assessment. However, observations of installed systems are not being widely recorded and shared in an organized, consistent manner; natural analogs are not yet well represented in system performance assessments; methods for adaptive updating are not well developed; and results are not widely deployed for feedback to improved CC&C systems.

Range of Applicability: All stewardship sites.

Needed R&D:

1. Compile results of current field tests for specific source-system-setting configurations, including pilot-scale and partially implemented systems, and compile performance predictions for systems in the design or planning stages. Provide this information in a *"performance assessment" resource report*.
2. Develop a *protocol* for the consistent recording of observed changes in installed systems, addressing all CC&C system components – including caps and other covers (e.g., considering crack formation, animal burrowing, and vegetation establishment), vertical and horizontal subsurface barriers, leachate collection systems, permeable reactive barriers, grouts, and water treatment media. Develop a *guide* for measuring the effects of these changes on system properties significant to performance, and develop a *process and tool* for sharing this information broadly (see T/T #9).
3. Develop *methods and tools* for iterative performance assessment, with an emphasis on the analysis of potential failures and related impacts as system and setting conditions change over time, using probabilistic and Bayesian approaches. Provide this modeling information in a *"performance assessment" reference handbook*.
4. Develop *methods and tools* for adaptively updating field test designs and refining analogs over time.
5. Develop *methods and tools* for integrating field test, analog, and performance assessment information to provide feedback for guiding system improvements (to prevent failures or offset impacts).
6. Develop an *approach and protocol* for triggering system upgrades that reflects combined input from the technical team and stakeholders, and provide these in tiered *guides* such as general primers complemented by field guides for site-specific implementation.

Links:

With All Other CC&C Capabilities:

- All three

With Other Work Groups:

- *M&S:* Solicit input on performance data from current system monitoring, and provide the resource report as scoping input for monitor and sensor development. Solicit input on methods for adaptive assessments, updated protocols with system feedback, and

determining indicator upgrades, and provide these methods and approaches as scoping input to M&S development.

- *SSIC*: Solicit input on adaptive performance assessment for safety systems and institutional controls, and solicit results of related stakeholder involvement activities. Provide the resource report and methods for adaptive assessments, including feedback and refinement, as scoping input for SSIC.
- *DMIP*: Solicit input on adaptive performance assessment for decision making and institutional performance, and solicit results of related stakeholder involvement activities. Provide the resource report and methods for adaptive assessments, including feedback and refinement, as scoping input for DMIP.

Sources:

Technique/Technology # 9 (Iterative Information Evaluation and Communication)

Title: Conduct Ongoing Data-Information Evaluation, Management, and Communication

Current Maturity Level: Methods for evaluating data and information, maintaining records, and refining systems are fairly well developed, as are standard communication methods. However, these have not yet been well integrated or deployed for long-term systems.

Range of Applicability: All stewardship sites.

Needed R&D:

1. Compile and synthesize the following in a “*stewardship information*” status report (e.g., to be regularly updated over >10-20 years to capture lessons learned and best practices for iterative refinement of processes and means being used at DOE stewardship sites).

Note: See * below for the types of data that could be included in stewardship reporting.

- a. Stewardship data being collected for CC&C systems, including from Grand Junction and other programs, and expectations for data from systems being put in place and those in the design and planning modes. Include: for what purposes these data are collected; data quality and traceability; platform, form and format; backup methods and processes (e.g., microfilm or duplicate files in regional and national storage); and methods or procedures used to define requirements for what data are collected and how they are evaluated (including how false positives, false negatives, and outliers are identified and managed), and use of meta data.
- b. Methods and tools being implemented and planned for managing data, information, and records transfer – addressing such issues as indexing, file compatibility, and feasibility and necessity of synchronization (many legacy databases are in outdated software, some may not warrant the effort it would take to include) notably for sites transitioning from active cleanup to stewardship. Include information from pilot projects for Nevada (database integration) and Grand Junction (information portal, geographic information systems [GIS], records management), as well as projects from Rocky and Ohio (records management).

- c. Methods and tools being implemented and planned for communicating stewardship knowledge, including accessibility (e.g., LTS website and other electronic means, administrative records or reading rooms in site areas, national storage file) and active dissemination over space, time, and audience accounting for different levels of operational need (e.g., site, local authorities, community, general public, other sites).
 - d. Current and planned roles and responsibilities for collecting, integrating, interpreting, communicating, transferring, and maintaining data, information, and records, e.g., a *steward's plan*.
 - e. What data that consider long-term implications are being incorporated into current environmental management decisions, and how this is being done (e.g., life-cycle analyses and cost tradeoffs and related decision-making tools).
2. Using this information as a foundation, conduct an updated *needs assessment* to identify parties with a need for or interest in stewardship knowledge, and solicit inputs – ranging from core information needs and approaches for defining these, to roles and responsibilities and general long-term plans for data, information, and records management including organizational and infrastructure measures and data integration.
3. Using results of 1-2, develop improved *methods and tools* for the following, and provide this information in a “*data identification, integration, & interpretation*” *resource handbook*
 - a. Defining core requirements; developing a flexible, comprehensive taxonomy (with general categories and specific data elements to accommodate both national and site-specific needs); integrating data acquisition (including from automated systems, laboratories, and observations recorded on paper); harmonizing measurement methods, network topologies, and programs; assuring and scoring data quality (e.g., through “fit-to-use” criteria developed from cost-benefit models, artificial intelligence methods, and statistical tools with graphical interfaces); evaluating time-dependencies (e.g., from diurnal to seasonal changes and beyond); developing flexible data structures (e.g., electronic formats) and processes for transformation (to a uniform basis), transfer (e.g., through teleinformatic networks), and storage (e.g., in a source database with a centralized warehouse and data marts); defining a distributed system architecture; archiving for both direct data access and automated, regular updating of interpretive plots, graphs, and thematic maps with intelligent interface (e.g., using a meta-base with standard vocabularies using expert systems and artificial neural networks)
 - b. Aggregating and interpreting raw data across system components, environmental resource types, and monitored parameters over space and time, including through integrated electronic data processing, GIS and adaptive visualization techniques, and use of meta-information or catalog systems with advanced query tools
 - c. Preparing interpretive summaries focused on the bottom line and tailored for different audiences (see 1c), to include background context and trend analyses, and considering server security (e.g., with firewalls)
 - d. Incorporating this information into CC&C system design, operation, and maintenance, such as through improved decision support system (DSS) shells (for which artificial intelligence shells are often the base technology) and simulation models to predict outcomes of proposed decisions, together with

access to materialized views of warehoused data (mindful of stored data security as needed, e.g., with Java Servlets).

4. Compile information management (IM) and information and communication technology (ICT) *methods and tools*, evaluate their evolution to date and projected advances (e.g., third-generation mobile/wireless communication with base stations and routers; flat screens versus cathode ray tubes), evaluate ICT equipment and application requirements and costs, and develop *plans* for adapting to IM-ICT changes over time (as these will certainly occur). Provide this information in an “IM-ICT” *reference report*.
5. Develop methods, processes, and tools for information communication, considering shared, layered, and open architectures and integrated infrastructures (with exchange formats and protocols, metadata harmonization, front-end data servers and application servers as generic model adapters for metadata systems), communication infrastructure (with registries for data definition and XML schemes, and for on-line information on servers; and a call server for managing communication between clients and the distributed system), simplified user interfaces (considering internet/intranet techniques); and tools for supporting priority data flows.
6. Develop optimization *methods and tools* to define umbrella and site-specific plans for managing data, information, knowledge, and records, with an emphasis on streamlining (to identify “min-safe” needs and non-resource-intensive processes to limit space, time, and cost requirements) and communicating priority information.
7. Develop improved *methods and tools* for soliciting feedback on this shared knowledge to identify system needs (including institutional components) and trigger responses, including approaches for linking with decision systems, such as multi-criteria spatial decision support tools.
8. Evaluate and develop improved *methods, tools, and procedures* for communicating failure-triggering events and conditions and potential consequences and their significance. For immediate threat situations, the communication component would include rapid notification of multiple parties by multiple means (redundant backups could include audio, visual, and active contact via smart-tags and automated activation of wireless technology). For non-emergency situations, this could lower-level broadcast, involvement, backup, and response triggers (e.g., similar to tornado watch and warning).

* For example, site information would be expected to include the following.

- a. Legal-compliance: regulatory standards and Orders; permits, licenses, authorizations, and certifications; withdrawals, leases, easements, rights-of-way, access and use restrictions; mining and water rights; tribal agreements; required effectiveness reviews, other agreement milestones and schedules
- b. Environmental setting: initial and post-closure, with trend analyses and background information
 - resources (characterization records): hydrology (surface, ground water); topography, soil, geology (geochemistry, geotechnical, geomorphology, seismicity); biota, succession; air, meteorology, climate; natural catastrophic events; historic, archaeological, cultural properties; land use, demographics, infrastructure, economics
 - contamination (monitoring records): nature and extent of residual contamination across environmental media, post-cleanup verification surveys

- c. CC&C systems:
 - siting and design basis, specifications and performance envelopes, drawings and as-builts, delineated system area with buffer zone, O&M plans, costs
 - contents: volumes, types / matrixes, concentrations, emplacement records
 - related infrastructure, transportation, safety records
 - d. Communication systems-plans: including roles and responsibilities, means
 - routine: information type & level, accessibility, dissemination, maintenance
 - emergency: notification and response, contingencies
-

Links:

With Other CC&C Capabilities:

- All three

With Other Work Groups:

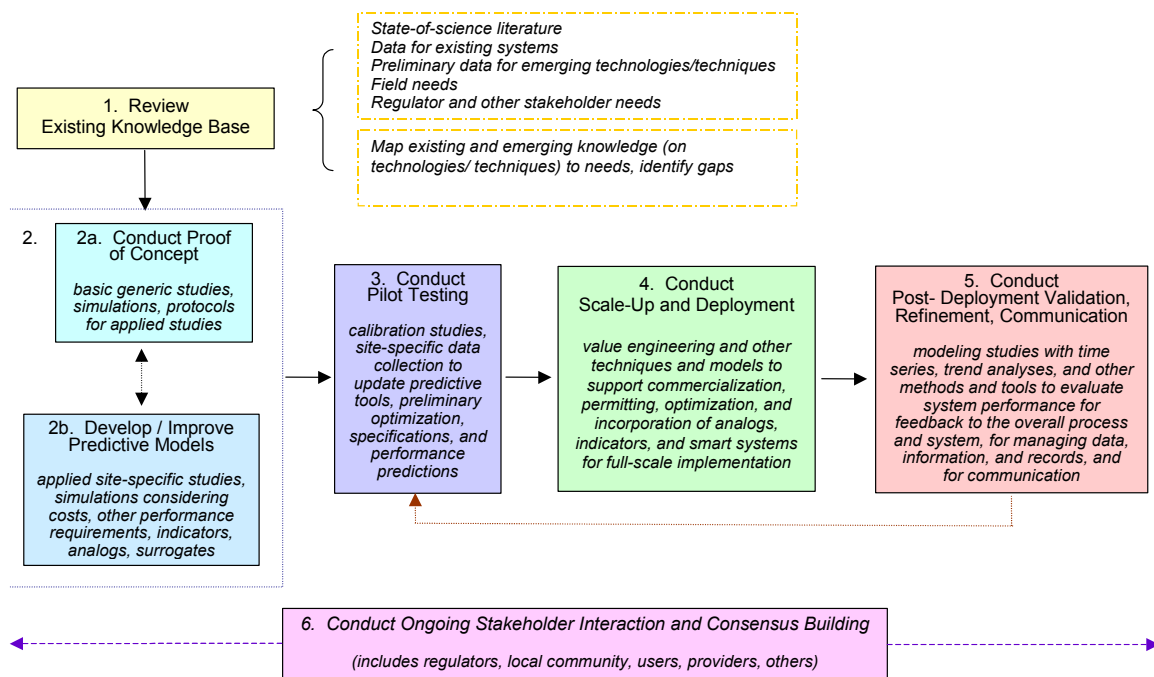
- *M&S:* As indicated above, solicit input to methods and tools and provide related information as scoping input to M&S development, evaluation, and refinement.
- *SSIC:* As indicated above, solicit input to methods and tools related to data, information, knowledge, and communication regarding safety systems and institutional performance, and provide summaries, methods, tools, and plans as scoping input to SSIC. Included is soliciting input on means for obtaining and incorporating stakeholder and other institutional inputs and lessons learned sharing information.
- *DMIP:* As indicated above, solicit input to methods and tools related to data, information, knowledge, and communication for decisions safety systems and institutional performance, and provide summaries, methods, tools, and plans as input to DMIP. Included is soliciting input on means for obtaining and incorporating stakeholder and other institutional inputs, lessons learned sharing information, and input on institutional frameworks and processes for IM and decision making.

Sources:

Technology Pathway Summary (Form B)

Capability to be improved: 4.1 Conceptualize and predict system performance and potential failure modes / levels of failure.

Associated Target(s): 4.1 Deploy a “toolbox” of techniques and technologies (e.g., models, natural analogues, guidance, performance indicators, failure criteria, etc.) to improve planning, decision making, design, monitoring, maintenance, and interpretation of monitoring data.



This pathway is closely tied to those for *Capabilities and Targets 1.4., 2.2, 5.1* and, therefore, includes elements also reflected in those pathways, as well as certain costs.

1. **Review Existing Knowledge Base.** This involves reviewing the existing scientific literature, site information, and other information sources, and interviewing site managers and their teams, research investigators, technology developers, other technique/technology users and providers, and stakeholders.

- ***Prerequisites***—None
- ***Expected Products/Results***—Status reports, lessons learned, and identification of gaps between existing resources and needs.
- ***Duration***—6-12 months, with this effort being conducted in parallel for the eight technique/technologies identified on Form A.
- ***Cost***—Should not exceed \$250K each, or about \$2M total. (Based on concentrated effort by ~1 senior/expert FTE-equivalent per technique/technology.)

2. (a) Conduct Proof of Concept. This involves evaluating existing methods and tools for relevance to CC&C systems being developed or considered (baseline and alternate) and identifying opportunities for improvement.
 - *Prerequisites*—Products of Step 1.
 - *Expected Products/Results*—Reference and resource reports.
 - *Duration*—6-12 months, with this effort being conducted in parallel for the eight technique/technologies identified on Form A.
 - *Cost*—Should not exceed \$150K each, or about \$1.2M total. (Based on concentrated effort by ~2/3 senior/expert FTE-equivalent per technique/technology type.)
2. (b) Develop and Improve Predictive Models. This involves improving predictive methods and tools to increase their applicability to CC&C systems being developed or considered (baseline and alternate), including linking models to reflect coupled processes. New field data collection is not part of this task. Model development focuses on enhancing and integrating existing models rather than creating new ones.
 - *Prerequisites*—Products of Steps 1 and 2a.
 - *Expected Products/Results*—Handbooks and resource guides.
 - *Duration*—6-12 months, with this effort being conducted in parallel for the eight technique/technologies identified on Form A.
 - *Cost*—Should not exceed \$150K each, or about \$1.2M total. (Based on concentrated effort by ~2/3 senior/expert FTE-equivalent per technique/technology type.)
3. Conduct Pilot Testing. This involves collecting and incorporating site information into the evaluation and development of updated, somewhat validated methods and tools. Targeted data collection can reduce major uncertainties in the models that will in turn significantly reduce design conservatism and associated costs for CC&C systems. The schedule and cost for this data collection is presented here because it represents activities in the field rather than paper or laboratory studies. (This main data collection effort is discussed under technique/technology #1 in Form A.)
 - *Prerequisites*—Products of Steps 1, 2a, and 2b.
 - *Expected Products/Results*—Initial site-specific models and other methods and tools.
 - *Duration*—6-24 months, with this effort being conducted in parallel for the eight technique/technologies identified on Form A.
 - *Cost*—Should not exceed \$4-5M. (Based on \$250-350K for targeted data collection at 10-12 key sites, with the balance going toward further enhancing and re-coupling models and other methods and tools.)
4. Conduct Scale-Up and Deployment. This involves extending improved methods and tools to full-scale site application for CC&C systems being developed or considered (baseline and alternate). Limited additional data collection may also be involved. A portion of this

step may overlap in time with Step 3, depending on the technique/technology type (e.g., for #9).

- ***Prerequisites***—Products of Steps 1, 2a, 2b, and 3.
- ***Expected Products/Results***—Improved site-specific models and other upgraded methods and tools that are more predictive and effective; site-specific design guides and protocols.
- ***Duration***—12-24 months, with this effort being conducted in parallel for the eight technique/technologies identified on Form A.
- ***Cost***—Should not exceed \$350K each, or about \$2.8M total. (Based on concentrated effort by ~1 senior/expert FTE-equivalent per technique/technology type, combined with limited additional data collection.)

5. **Conduct Post-Deployment Validation.** This involves evaluating and further refining predictive models and other methods and tools in light of actual system performance.

- ***Prerequisites***—Products of Steps 1, 2a, 2b, 3, and 4.
- ***Expected Products/Results***—Lessons learned, refined site-specific models and other methods and tools, and improved protocols and procedures.
- ***Duration***—12-24 months and longer (design life), with this effort being conducted in parallel for the eight technique/technologies identified on Form A.
- ***Cost***—Should not exceed \$250K each, or about \$2M total. (Based on concentrated effort by ~1 senior/expert FTE-equivalent per technique/technology.)

5. Maintain System Performance

Technical Approaches (Form A)

Capability to be improved: 5.1 Identify and implement improved responses to change (via routine and preventative maintenance that nurtures system performance) and failure (via corrective repair, retrofit, and replacement).

Associated Target(s): Deploy technologies and protocols that significantly reduce the need for maintenance intervention (and cost) of installed contamination containment and control system.

Technique/technology # 1

Title: Long-lived water treatment media

Current maturity level: The maturity level depends on the kind of water treatment is being done. For example, treatments needed for municipal supply of water are very mature. Problems of limited, special or complex nature, in groundwater are in the development phase. The water treatment media must be evaluated in the whole treatment system, including the regulatory aspects, transportation, disposal pathways, etc. For example, In some cases, longer lived water treatment media will mean the media will have a higher concentration of the contaminant, which may severely limit or prevent economic disposal options. Much research is going on in the formal term for this science, “separations”.

Range of Applicability: All saturated zone applications involving in situ or ex situ water treatment.

Needed R&D: R&D needed is in the area of getters for contaminants that drive risk. For example, Tc99 is the risk driver for most DOE nuclear waste site, including Yucca Mtn.

Sources:

http://www.nap.edu/html/groundwater_improving/
<http://www.em.doe.gov/define/techs/rp-insit.html>
<http://www.epa.gov/ogwdw000/ars/treat.html>
<http://www.epa.gov/water/>
<http://www.wttac.unh.edu/>
<http://www.em.doe.gov/define/tables/t42.html>
<http://www.em.doe.gov/define/techs/techdes4.html#38>
<http://www.nmt.edu/mainpage/news/subsur.html>
<http://www.frtr.gov/optimization/singh.html>
<http://www.frtr.gov/optimization/streckfuss.html>

Technique/technology # 2

Title: Self-healing covers and caps. Alternatives to traditional caps and covers

Current maturity level: High for to RCRA subtitle C and D, low for alternatives (ET covers, graded covers, etc)

Range of Applicability: All climates and conditions.

Needed R&D: Most of the research is needed in the combination of alternative covers and caps and failure analysis. To design self-healing systems, we need to find out what the performance envelopes are for the alternatives (RCRA C and D are found to fail at a high rate, and failure modes are understood). We need to find out how alternative caps behave at the limits of environmental conditions and for acute events that may occur only on 100 – 1000 yr timeframes. We particularly lack long-term data sets on cap performance, or natural analogs. Development of synthetic materials, or identification of natural materials and their combinations that would enhance performance is a consequence of the R&D into alternatives and natural analogs and the failure mechanisms.

Sources:

<http://128.219.128.87/default.asp>

<http://www.em.doe.gov/rapic/9links.html>

Technique/technology # 3

Title: Grouts for in situ stabilization control

Current maturity level: Medium to High. Grouts are very advanced in applications in the mining, oil and water drilling/well completion areanas. Grouts for contaminant control and stabilization are not yet mature for EM applications.

Range of Applicability: control of movement of contaminants in the subsurface, both saturated and vadose zones

Needed R&D: Emplacement, and verification of proper emplacement. Determination of final performance of grouts installed wet into the vadose zone (ultimate desiccation of materials). Performance and integrity confirmation of grouts, especially deep emplacements and where complex geometries are required.

Sources:

<http://www.nap.edu/books/0309056853/html/>

http://www.cmst.org/OTD/tech_summs/In_Situ_Rem/In_Situ_chap1.html

<http://www.doegjpo.com/perm-barr/>

<http://www.rtdf.org/public/permbarr/default.htm>

http://es.epa.gov/ncer_abstracts/centers/hsrc/bioremed/eval.html

<http://www.nwer.sandia.gov/wlp/capabilities.htm>

Technique/technology # 4

Title: In situ and ex situ regeneration of water treatment media

Current maturity level: Low to high: See technology technique # 1

Range of Applicability: All saturated zone applications involving in situ or ex situ water treatment.

Needed R&D:

Sources:

<http://www.groundwatersystems.com/bioprimr.html>

<http://www.frtr.gov/optimization/optimize.html>

<http://www.engg.ksu.edu/HSRC/97abstracts/doc72.html>

<http://www.dial.msstate.edu/monthlies/feb01.html>

Technique/technology # 5

Title: In situ flushing of leachate collection piping/trenches

Current maturity level: High for industrial-like leachate collection systems. Low for trenches, other non-pipe like transfer systems

Range of Applicability: Engineered disposal facilities

Needed R&D: For industrial-like collection systems, testing and possible modification of commercial systems. For trenches, and other non-pipe like structures, research into fouling mechanisms and design of facilities to facilitate regeneration.

Sources:

<http://www.hcet.fiu.edu/r&d/tfa/unplugging/default.asp>

Technology Pathway Summary (Form B)

Capability to be improved: 5.1 Identify and implement improved responses to change (via routine and preventative maintenance that nurtures system performance) and failure (via corrective repair, retrofit, and replacement).

Associated Target(s): Deploy technologies and protocols that significantly reduce the need for maintenance intervention (and cost) of installed contamination containment and control system.

To achieve target 5.1, the LTS CC&C working group consolidated the traditional waterfall model into the following technology development pathway:

1. **Review existing knowledge base.** This includes the traditional waterfall model steps of: concept and feasibility. In the traditional model, concept is the step where you identify that you do not have the technology you need, or the technology that is available is inadequate. It is the realization that you are sub optimized in some way. This first step includes the following elements:
 - a. Feasibility is a preliminary exploration of solutions that fit the physical processes (the physics of the problem).
 - b. Some preliminary evaluation of costs and technical viability of alternate solutions is done.
 - c. A review of the technologies available in the market place.
 - d. An evaluation of the state of the development of applicable technologies is performed, along with some investigation of the availability of suppliers of such technology.
 - e. an assessment of life-cycle requirements for support, maintenance, technological obsolescence, among other factors affecting life-cycle costs of a solution.

Time in this step will be relatively short, given that much information and experience has now been gained in the progress of EM activities over the past few years. This step should not take more than a few weeks and range in the thousands of dollars.

2. **Proof of concept – theoretical and bench scale.** This step incorporates the traditional waterfall model steps of user definition of requirements, developer definition of requirements and high-level design. The proof of concept step contains the following elements:
 - a. The user documents as much as he knows about the job the system must do. He may also specify schedule and cost constraints
 - b. Special constraints, e.g. run on an specific platform; all supplementary requirements: documentation, maintenance, quality, standards
 - c. Compliance, intermediate reviews
 - d. Developer analyses of user requirement and performs further investigation of requirements, produces developers version of requirements
 - e. Integration of developer and user system requirements document.
 - f. Technology development plan
 - g. Subsystem specification and design
 - h. Cost, schedule analysis.

This step is one of configuration requirements and planning and engineering analysis for hardware development. This step should not take more than weeks to a few months, and cost in the range of thousands of dollars.

3. **Site-specific treatability testing.** This step incorporates the traditional waterfall model steps of prototype development and integration and test. This step includes the following elements:

- a. An initial working prototype is developed and made to work on a bench scale.
- b. Proof of principle is established in the general case
- c. Components and modules are brought together to form higher level systems.
- d. The bench scale process is tested against a specific user problem or scenario
- e. Scale-up issues are evaluated

This step is highly uncertain, and may require weeks to months. The costs, depending on the technology being developed, can run from a few hundred dollars to a few million.

4. **Pilot scale testing.** This step incorporates the traditional waterfall model step of system test. This step includes the following elements:

- a. A fully integrated prototype system is developed and tested on a small scale
- b. System performance boundaries are explored, including failure modes (if practical)
- c. Maintenance and usability issues are explored
- d. Risk analysis
- e. Cost, schedule analysis.

This step is also highly uncertain, and may take between days up to months. The costs, depending on the technology being developed, can run from a few hundred dollars to millions.

5. **Deployment.** This step incorporates the traditional waterfall model steps of systems test and part of acceptance test. This step includes the following elements:

- a. Full scale up of system
- b. Initial tests in actual end-user environment
- c. Exploration of actual full-scale end-user environment performance envelope.
- d. Exploration of usability, which may include such things as operator interface evaluation, health and safety, integration with other site systems
- e. Initiate process of system refinement
- f. Risk analysis
- g. Cost, schedule analysis.

This step will take a few months, often for at least 6 months to obtain a range of environmental conditions. Deployment may cost between a few thousand to hundreds of thousands of dollars.

6. **Monitor and validate field effectiveness.** This step incorporates the traditional waterfall model of acceptance test (part of acceptance was accomplished in step 5) and operations. This step includes the following elements:

- a. Further exploration of usability, and performance envelope

- b. Continue system refinements
- c. Develop criteria and put a program in place to evaluation long-term system performance
- d. Further evaluate failure modes and their interaction with other site systems.

The time for this step will often take at least 6 months, much as the previous deployment step. The costs should be less than the deployment step, but still range up to hundreds of thousands of dollars.

7. **Confidence building and institutional acceptance.** This incorporates the traditional waterfall model of operations (part of operations was accomplished in step 6) and maintenance. This step includes the following elements:
- a. Institutionalizing the new technology
 - b. Building acceptance of the new technology externally
 - c. Defining long-term operability processes
 - d. Defining failure mode prevention actions (preventative maintenance at the minimum)
 - e. Defining long-term operations and maintenance costs
 - f. Evaluation of useful life (replacement analysis)
 - g. Risk analysis.

This step is highly variable, and may take weeks to months. Cost should range in the tens to hundreds of thousands of dollars.

Discussion:

Although the waterfall model has been traditionally used in EM-50, there have been numerous studies that indicate inadequacies of the model for the high-risk, high cost baselines. Specifically, the *DOE Research and Development Portfolio, Environmental Quality, 2000* (DOE 2002) explores this issue:

“One analytical tool in portfolio management is the maturity gate model. The model describes a linear progression from basic research through deployment. This model has been validated by experience in industry and in some federal research and development efforts. Money can be saved by testing hardware and/or processes at pilot, bench, and demonstration scales before deciding to proceed with deployment. The model works well in these well-defined and controlled situations. However, the cleanup program requires solutions that go beyond the development of a specific piece of hardware or process. In these instances the linear model is not always applicable. The exceedingly complex nature of the cleanup problems makes solution development an ongoing process. For example, during the deployment of a solution to a remediation problem we find that additional fundamental knowledge, such as reaction rates or partitioning coefficients, is required. Directed basic research must be provided to support the deployment of the solution. Research and development in an environment like this requires investments that support each phase: research, development, demonstration and deployment. This model is nonlinear. Investments may be required simultaneously at different gates, and the results of all these investments must be integrated. Investment decisions based on this nonlinear model are often different from those based on the linear approach.”

There are numerous models that can be applied. One model that is likely to be most effective in the high-risk high-cost baselines is the Spiral development model. The Spiral Development Model (see Boehm, 1988, for instance). This development model in its most simplified version (see Figure 1) builds systems and complexities on life-cycle objectives.

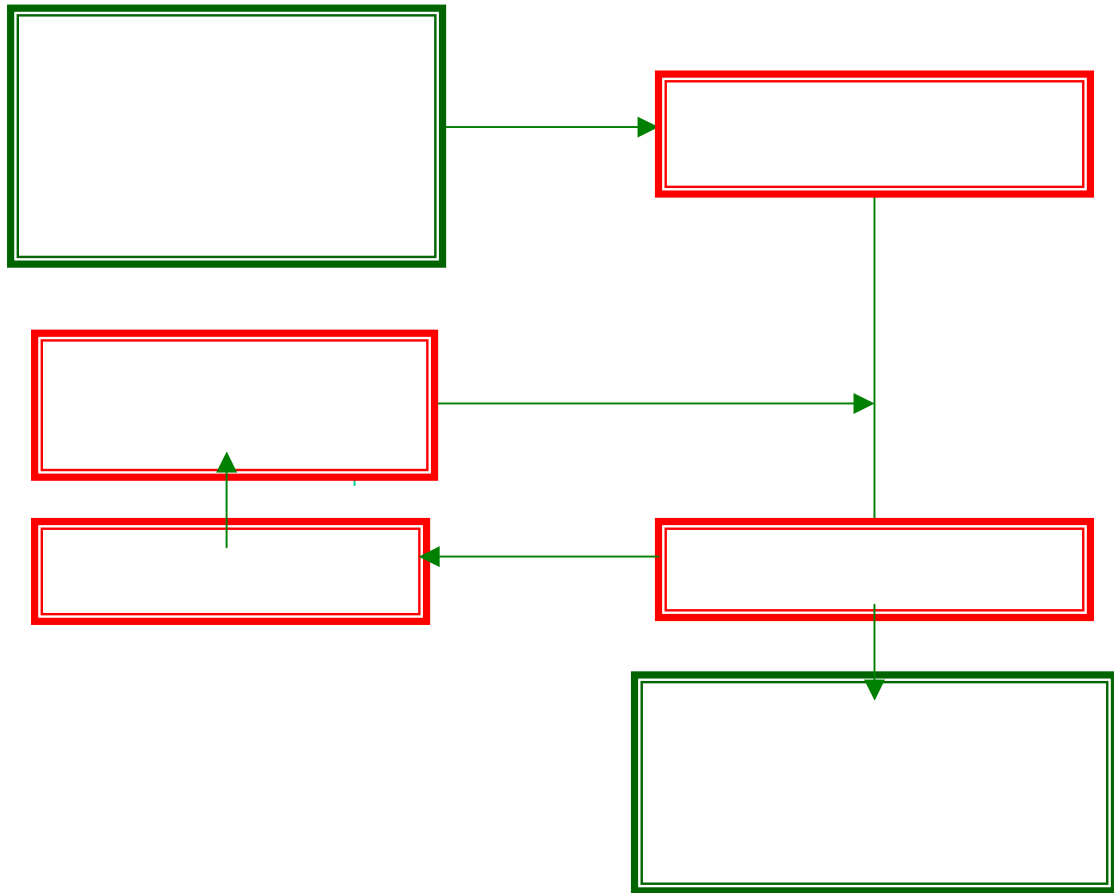


Figure 1. The Spiral Development Model

The Spiral Model for rapid prototyping has the following characteristics:

- The phases of the traditional “waterfall” development model are visited iteratively in several cycles of prototyping. This is appropriate for large projects of an innovative nature where technical risks can dominate.
- A small-scale prototype is developed early in the design process in order to test out key design elements of large-scale projects.
- During early iterations, the incremental implementations might be prototypes in nature. During later iterations, increasingly more sophisticated engineered systems are produced.
- Development is shortened the faster one can go around the spiral to reach full system capability.

The Spiral Model is becoming increasingly popular for minimizing the cost and time of development activities, while increasing suitability and usability of the end product. It relies critically, of course, on vertical integration from researcher through applications testing.

Spiral Model Elements of Time and Cost

The Spiral Development Model showing all of its elements and progression are shown in Figure 2. Figure 2 as shown is for software development, but any technology development activity can use the model with only an alteration of activity names.

Each cycle starts with objectives, alternative and constraints. Defining these elements should not take more than a few days to a few months. The cost can range from a few thousand dollars to hundreds of thousands.

The next step is the risk analysis. This includes technical risks, market risks, financial risks, and prototyping risks, among others. This step will take from a few days to months. The cost can range from a few thousand dollars to hundreds of thousands.

The next step is prototype development. This step is highly uncertain, and may require weeks to months. The costs, depending on the technology being developed, can run from a few hundred dollars to millions.

The next step is testing and evaluation. This step is also highly uncertain, and may take between days up to months. The costs, depending on the technology being developed, can run from a few hundred dollars to millions.

The next step is adding complexity to the prototype to meet the next level of performance requirements, and review the results of all previous steps. This step will take weeks to months, and may cost hundreds to thousands of dollars.

The cycle then begins again, and includes all the elements previously noted, and as one nears the fully developed system, includes such things as final acceptance testing. Each trip around the spiral addresses four fundamental steps: (1) Determine objectives alternatives and constraints, (2) evaluate alternatives, identify and resolve risks, (3) develop and verify next level of complexity in the evolving prototype or system, and (4) plan the next phases of development based on review of previous results.

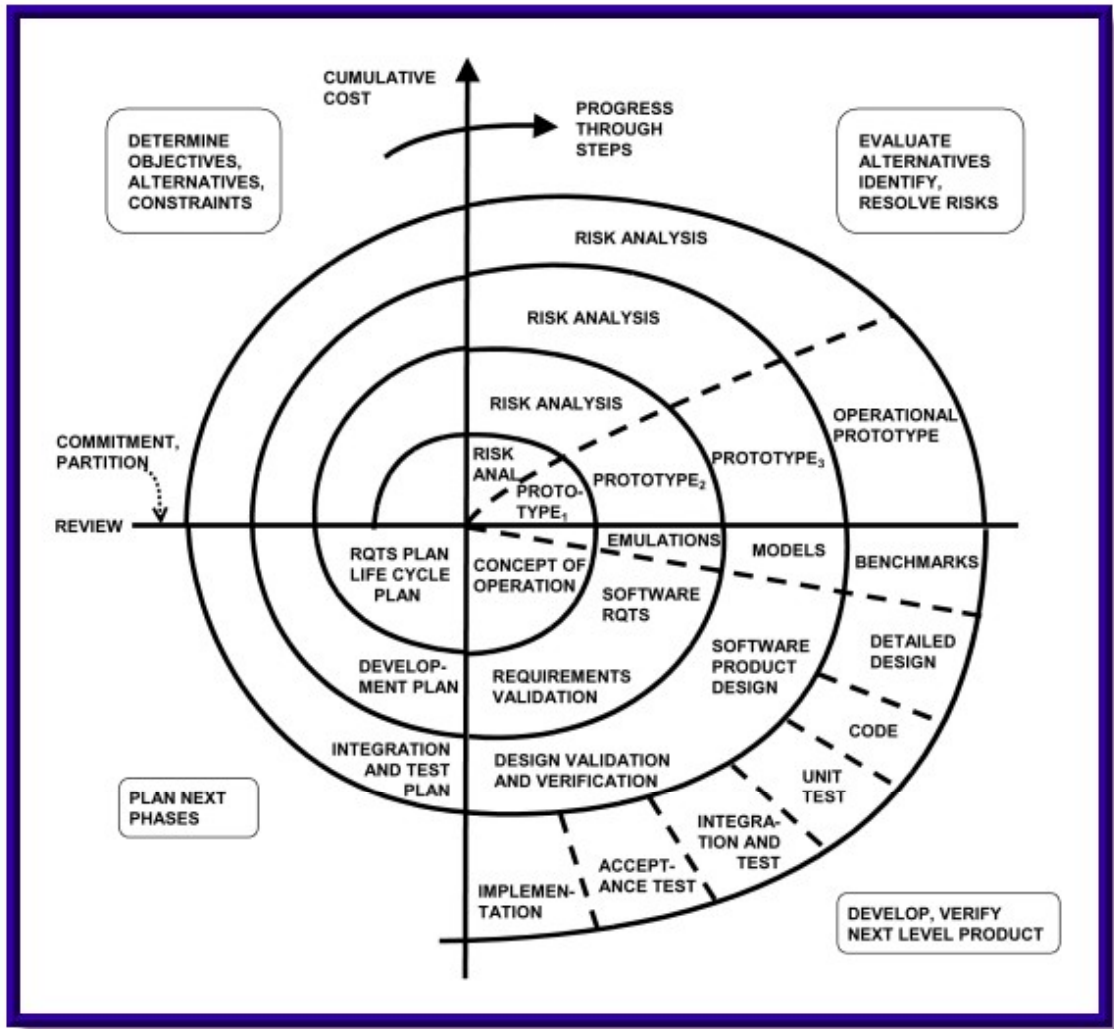


Figure 2. Spiral Development Model (as depicted for software development)